ELECTRIFICATION OF DOMESTIC HOT WATER TO AID THE INTEGRATION OF RENEWABLE ENERGY IN THE CALIFORNIA GRID

By

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ABSTRACT

ELECTRIFICATION OF DOMESTIC HOT WATER TO AID THE INTEGRATIOIN OF RENEWABLE ENERGY IN THE CALIFORNIA GRID

Alejandro Cervantes

Water heating in residential buildings, also known as domestic hot water (DHW), is the third largest use of energy after appliances and space conditioning. About 90% of the residential buildings in the state use natural gas fueled water heaters, 6% use electricity, and a small percent use liquefied petroleum gas (LPG) or solar water heaters. The current energy use associated with residential water heating is small relative to the total amount of energy consumption in the residential building sector, but it is still a contributor of greenhouse gas (GHG) emissions. Improving hot water systems can be beneficial for bill customer savings, energy use, and water savings.

Heat pump water heaters (HPWH) can function as grid batteries by using the water tank capability of thermal storage. The use of aggregated electrical DHW systems to store extra electricity during peak generation times or during low utility time of use (TOU) rates has the potential to alleviate some of the curtailed renewable energy power generation sources in the California grid while reducing carbon emissions and customer cost.

Water heating technology was simulated using the Building Energy Modeling software California Building Energy for Code Compliance (CBECC-Res) and the

California Simulation Engine (CSE). Different climate zones were explored to compare the electricity needed for a water heater operation given the same input parameters of water draw profiles and building envelope. The results show the feasibility of using HPWH and ERWH technology to participate in demand response management programs. The demand response capability of HPWH and ERWH show that they could be useful tools to accommodate surplus energy from solar generation during the solar peak hours. Whether the demand response is implemented using traditional HPWH or ERWH units, the capability of the technology to act on control signals is a necessary condition for a successful program.

ACKNOWLEDGEMENTS

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ACRONYMS

HPWH	Heat Pump Water Heater
NGWH	Natural Gas Water Heater
ERWH	Electrical Resistance Water Heater
COP	Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
CEC	California Energy Commission
CPUC	California Public Utilities Commission
DHW	Domestic Hot Water
TMY	Typical Meteorological Year
EF	Energy Factor
UEF	Uniform Energy Factor
FHR	First Hour Rating

INTRODUCTION

Water heating in residential buildings, also known as domestic hot water (DHW), is the third largest use of energy after appliances and space conditioning. DHW accounts for approximately 25% of the total energy consumption in the California residential building sector (EIA, 2009). About 90% of the residential buildings in the state use natural gas fueled water heaters, 6% use electricity, and a small percent use liquefied petroleum gas (LPG) or solar water heaters (CEC, 2016). The current energy use associated with residential water heating is small relative to the total amount of energy consumption in the residential building sector, but it is still a contributor of greenhouse gas (GHG) emissions. Improving hot water systems can be beneficial for customer bill savings, energy use, and water savings (PIER, 2013).

Historically, the California Public Utilities Commission (CPUC) and the California Energy Commission (CEC) enacted energy efficiency policies to reduce electricity consumption and encourage on site use of natural gas (Mahone, Li, Subin, Sontag, & Mantegna, 2019). Natural gas is primarily methane (CH_4), which has a higher energy content compared to other fossil fuels, and thus, it has a relatively lower carbon dioxide (CO_2) to energy content (EIA, 2018). However, natural gas is still a carbon intensive fuel. California's recent climate action plans, future standards, and building goals will have a profound impact on the residential building industry over the next decades, and it is expected that new residential buildings will be fueled by electricity (Young, Shiau, & Kristjasson, 2016).

Fuel switching DHW systems from natural gas to electrical resistance water heaters (ERWH) and heat pump water heaters (HPWH) can help reduce emissions and methane leaks associated with the use of natural gas water heaters (Raghavan & Wei, 2017). Previous research has demonstrated the potential of ERWHs to provide significant grid stability and control benefits through demand side management strategies (Diao, et al., 2013), however, it is important to understand the characteristics of HPWHs and how these characteristics will impact demand response programs and grid stability in the future. In 2015, new US Department of Energy efficiency standards require new residential water heaters larger than 55 gallons to have a minimum Uniform Energy Factor (UEF) greater than 2.0, effectively requiring them to be HPWHs (CFR, 2012).

One of the objectives of electrifying water systems is to reduce the use of fossil fuel consumption, however, if the electricity used for HPWHs comes from a carbon intensive power plant then the fuel switch at the end use (residential buildings) may paradoxically result in higher emissions. This can be avoided if electricity used for water heating systems comes from renewable sources (Hong & Howarth, 2016). With the integration of renewable energy sources into the California grid there is also an opportunity to capture the mismatch energy from solar and wind power production for a later use in residential demand. The electrification and the grid interactive control of electrical DHW systems has the potential for decarbonization, grid management, and thermal energy storage. HPWHs furthermore have the potential to decrease electricity use of residential water heating compared to resistance heaters. However, the use of more efficient heat pump technology may impact the potential to perform some grid services.

1.1- Thesis statement

Heat pump water heaters (HPWH) and electric resistance water heaters (ERWH) can function as grid batteries by using the water tank capability of thermal storage (Raghavan & Wei, 2017). The use of aggregated electrical DHW systems to store extra electricity during peak generation times or during low utility time of use (TOU) rates has the potential to alleviate some of the curtailed renewable energy power generation sources in the California grid while reducing carbon emissions and customer cost.

1.2- Implications of Research

Decarbonizing the residential hot water sector in California can help reduce the amount of GHG emissions and help the integration of renewables into the grid by providing thermal capability storage. The cost of the fuel switch will depend on the future cost of heat pump technology, electricity rates, and hot water consumption (Raghavan & Wei, 2017). The opportunity for demand response and demand shifting depends on climate zone, water heater type, water use profile, and utility rates. This study will also explore and identify the limitations of the use of open source software and building energy modeling for HPWH simulations. Utilities and efficiency advocates encourage the adoption of HPWHs, however, there is limited understanding of the potential (Widder, Parker, Petersen, & Baechler, 2013) and this research will add to the knowledge base on potential for responsive water heaters.

BACKGROUND AND LITERATURE REVIEW

2.1- Domestic Hot Water

Residential water heating, also known as domestic hot water (DHW), accounts for a significant share of the residential building sector energy consumption (Figure 1). Domestic hot water is potable hot water that is consumed for domestic purposes including food preparation, personal hygiene, and cleaning.

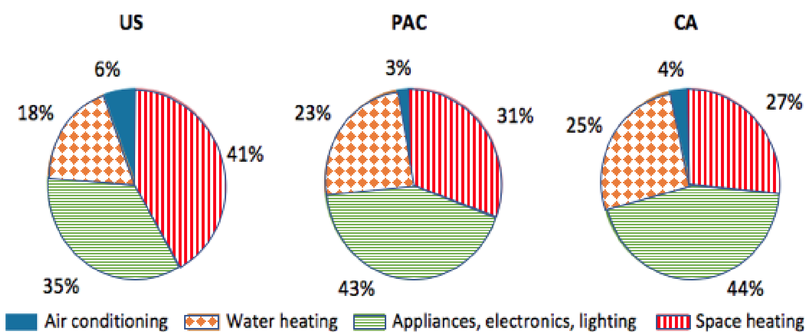

Figure 1. Household energy consumption by end use in the United States (US), Pacific Coast (PAC), and California (CA). California has a milder climate than other areas of the United States, and space heating and air conditioning make up a relatively small portion of energy use in the state. (EIA, 2009)

The total energy use associated with water heating is based on the end use, the number people and dwelling units on a household, water heater type, fuel type, distribution system, system efficiencies, and conditioned space area. Hot water draws at the end use points (showers and faucets) represent the useful energy consumed. Roughly 90% of California low rise residential buildings use natural gas water heaters, typically a storage tank system with volumes of 40 to 50 gallons. Standby losses represent about

25% to 35% of typical gas storage water heater systems annual energy use (Figure 2). Most residential building use either a natural gas or electric storage water heater, however, there are other higher efficiency water heating options available. These options include tankless water heaters also known as instantaneous or point of use, heat pump water heaters, and solar water heaters. These water heater types can be more complicated than a gas or electric storage water heater. Many factors impact the actual performance and efficiency of these models, such as the mains temperature, location of the water heater, and the daily draw volume and profile of a residence (NREL, 2013).

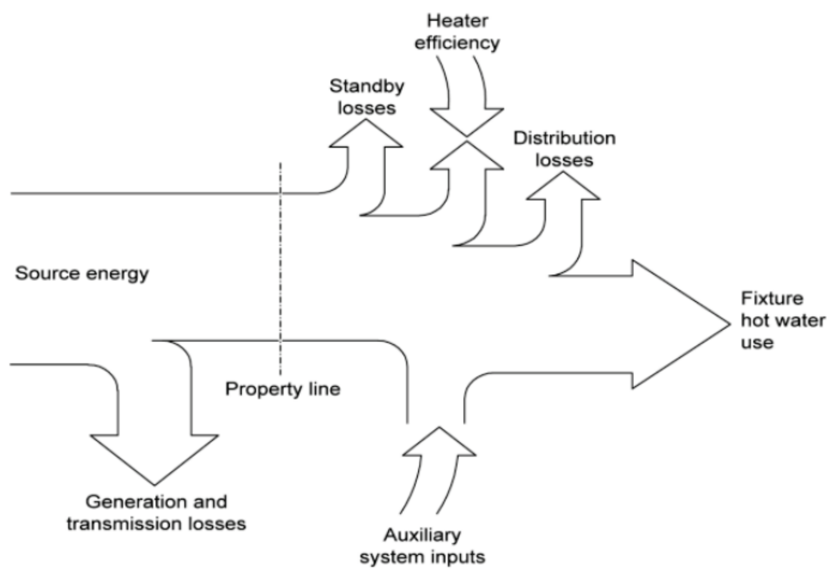

Figure 2. Water Heating Energy Flow Representation (CEC, 2017).

The energy associated with the hot water heater use remains relatively constant throughout the year, unlike the energy associated with space heating and space cooling, which is associated with weather patterns. Some places like Arcata in Climate Zone 1 do not have a cooling load due to the relatively low temperatures during the summer months (Figure 3). However, places in southern California such as Los Angeles in Climate Zone 6 and Climate Zone 9 do experience higher cooling load profiles during the high summer months (Figure 4). The possibility of demand response all year in residential buildings can be more feasible with water vs. space heating due to the constant use of energy for water heating throughout the year.

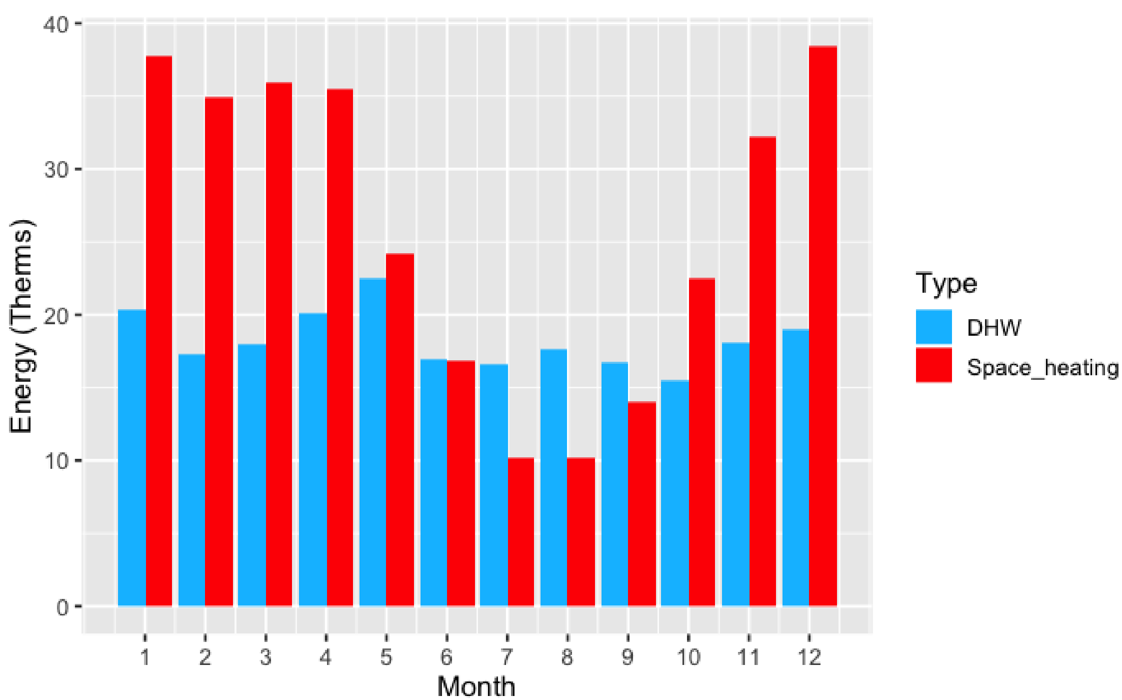

Figure 3. Natural gas consumption for space and water heating for a single-family residential building in Climate Zone 1.

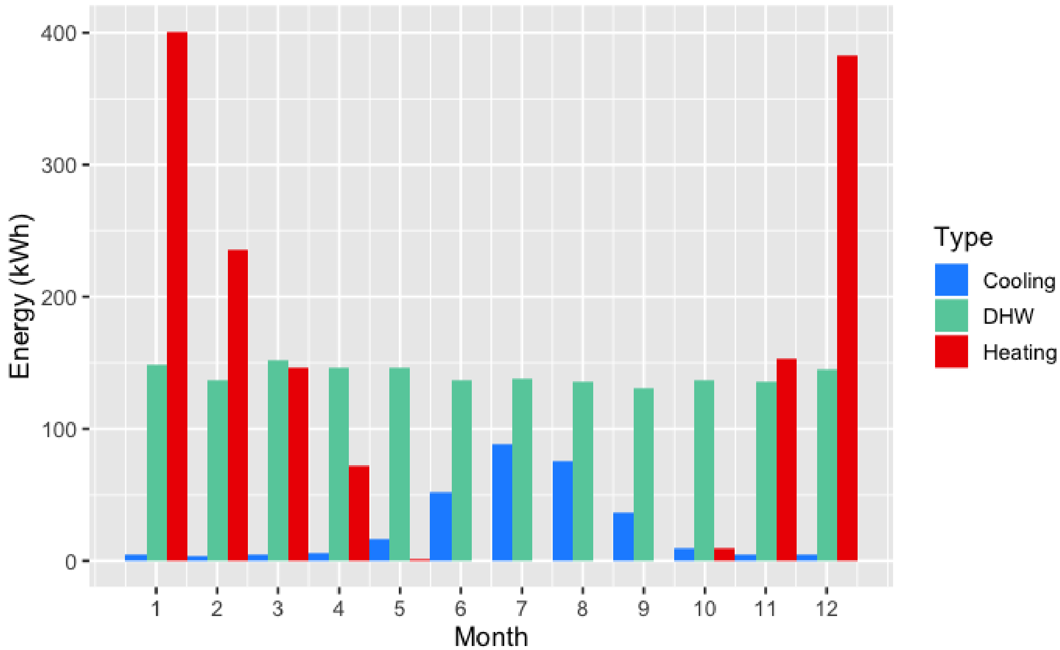

Figure 4. Electricity consumption for space heating, space cooling and water heating for a single-family residential building in Climate Zone 6.

2.2- Natural Gas Storage Water Heaters

The most common system in residential buildings is the natural gas storage water heater (Figure 5). These heaters are also the least efficient systems with a minimum efficient factor (EF) of 0.58 for a 50-gallon unit (DOE, 2018). The low efficiency is attributed to the combustion efficiency of turning natural gas into heat and to the standby losses of the storage tank and distribution. Since water is constantly heated in the tank, energy can be wasted even when a hot water tap is not running. Some storage water heaters have heavily insulated tanks, which can significantly reduce standby losses and lower operating cost (DOE, 2019). A natural gas storage water heater works with a thermostat that controls the temperature of the water inside the tank. Normally, the user can set the temperature anywhere between 120- and 180-degrees Fahrenheit (49 to 82 degrees Celsius).

The gas storage water heater works by convection. Cold water is supplied from the water lines to the bottom of the tank, where the water starts to warm. The heating mechanism, in this case a gas burner, stays on until the water reaches a certain temperature. Water exiting the water heater at the top is always the hottest in the tank at any given moment because it’s the nature of hot water to rise above denser, cold water. Since cold air and cold water are denser than hot air or hot water, the cold water settles at the bottom of the tank until it is heated by the burner. Then it is heated enough to rise (through convection) to the top of the tank where the hot water discharge pipe is located.

The hot water discharge is what supplies all the end use fixtures such as sinks, tubs, showers, and appliances that need hot water (Brain & Elliott, 2019).

The natural gas is supplied into a gas burner at the bottom of the tank. There is a control module that serves as a thermostat for the water heater that also controls the ignition of the pilot light. Natural gas water heaters also have an exhaust flue that serves two purposes. It exhausts combustion gases from the burner and serves as a heat exchanger that helps to heat water in the storage tank. A safety feature of the hot water heater includes a pressure relief valve and a discharge pipe. The purpose of the valve is to release excessive temperature or pressure build-up inside the tank. The purpose of the discharge pipe or drain valve is to drain the tank to prevent buildup of sediments in the bottom of the tank (Formisano, 2018).

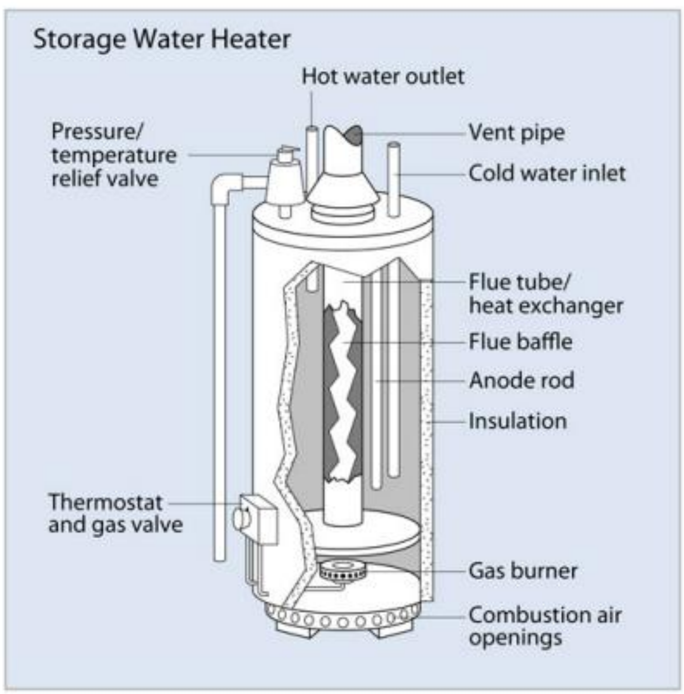

Figure 5. Natural gas storage water heater. (DOE, 2011)

2.3- Heat Pump Water Heater Technology

An air source heat pump water heater (ASHPWH) uses electricity to transfer heat from the ambient outside air to water in a storage tank. HPWHs can achieve higher efficiency values compared to other water heating systems because they can move heat rather than directly generate it (DOE, 2018). At the same time the HPWH dehumidifies the air around the unit, therefore operating also as a dehumidifier. This can be beneficial when the HWH is in a basement and/or in a humid climate.

Most residential HPWHs use air as a heat source, but other heat sources could be used such as water or the ground. Typical efficiency values for HPWHs are expressed in terms of the coefficient of performance (COP) and range between 2-3 COP. HPWHs have a significant market in Japan, where some HPWs can achieve a COP of 4 or higher (Hashimoto, 2016). The Coefficient of Performance (COP) is the ratio of thermal energy delivered by the HPWH to the electrical energy used to produce DHW; a higher COP represents higher efficiency.

HPWHs typically feature both a heat pump and an electric resistance element for heating (Figure 6). If the heat pump cannot keep up with the load or of the ambient air conditions prevents it from running, then the backup electric resistance elements will turn on. How often the electric resistance elements must be used depends on climate and hot water use. HPWHs typically have higher initial cost than conventional storage water heaters. However, they have lower operating costs, which can offset the high initial and installation costs.

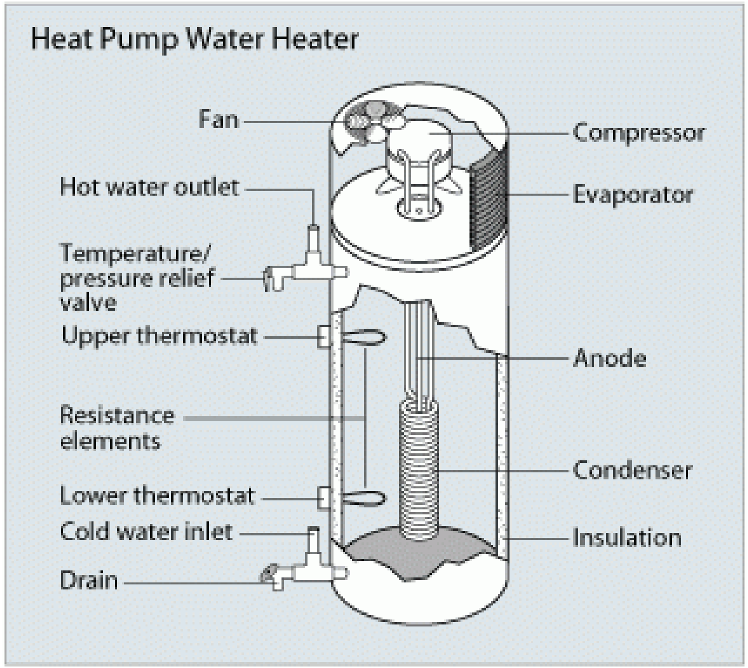

Figure 6. Heat Pump Water Heater (DOE, 2011).

Heat pump water heaters operate using the vapor compression cycle (Figure 7). In this cycle, a fan moves ambient air through an evaporator (air heat exchanger) to heat a working fluid, the heat pump refrigerant. The refrigerant picks up the ambient energy and goes through a phase change from low quality saturated mixture into a saturated vapor. The refrigerant then passes into a compressor where it increases its pressure and its temperature. Then, in the condenser (water heat exchanger), the refrigerant enters as a superheated vapor and transfers its heat to the water in the storage tank. The refrigerant then cools down into a saturated liquid and passes through an expansion valve, where the pressure and temperature are reduced, and the cycle starts over (Cengel, 2008).

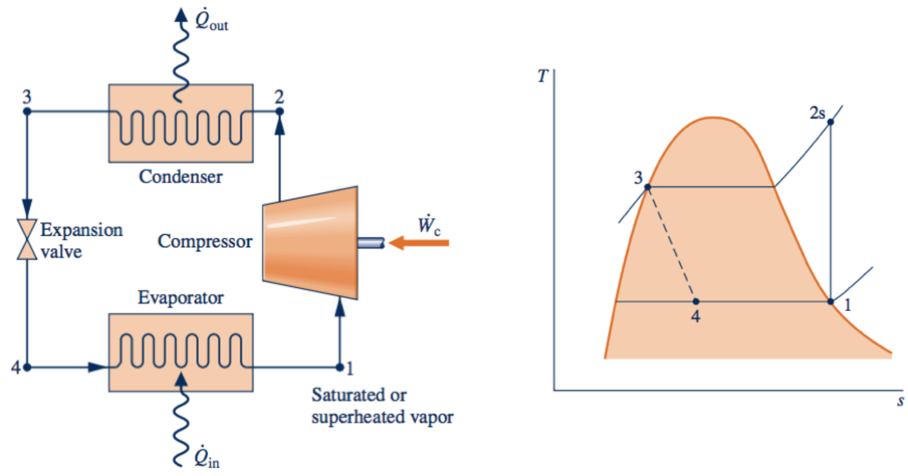

Figure 7. Schematic and Temperature – Entropy diagram for an ideal vapor compression cycle (Moran & Shapiro, 2014).

The actual vapor compression cycle (Figure 8) differs from the ideal case in that it experiences fluid friction which causes pressure drops and heat transfer to or from the surroundings. The compression process in the ideal cycle is isentropic, but due to friction effects the entropy of the process in an actual cycle will not be constant. Instead, the entropy of the compression process increases from state 1 to state 2 (Cengel, 2008).

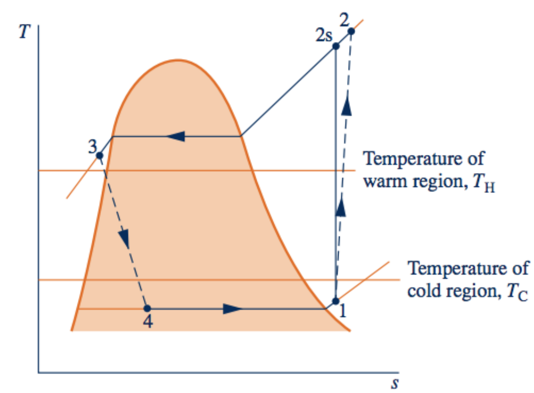

Figure 8. Temperature – Entropy diagram of an actual vapor compression cycle (Moran & Shapiro, 2014).

2.4- HPWH Sanden CO_2

Air source HPWHs are less efficient in cold climates since they need to extract heat from the surrounding air. However, newer models using carbon dioxide (CO_2) as the refrigerant can achieve higher efficiency in colder climates and can generate higher water output temperatures (Sullivan, 2017). R744 (CO_2) is a natural refrigerant that has a relatively low Global Warming Potential (GWP) and does not deplete the ozone layer (Sanden, 2018). R744 refrigerant has emerged as a viable refrigerant for heat pump technology. It has multiple advantages over other refrigerants including zero toxicity and flammability. The technology became popular in the 1990s in Japan, and currently Japanese manufactures have commercialized residential CO_2 HPWHs (Nawaz & Shen, 2017). Most of the R744 HPWH units are mini split systems, meaning that the evaporator and gas cooler are installed outdoors and the storage tank indoors.

The R744 refrigerant operates in a supercritical cycle due to the low critical temperature of CO_2. The HPWH operates at a cycle where heat is rejected by cooling CO_2 vapor at a supercritical pressure (Stene, 2016). The phase diagram of CO_2 (Figure 9) shows that the supercritical portion of the refrigerant is above 73 atmospheres (atm) and 31°C. In the cycle, (Figure 10) the heat rejection process occurs above the critical point, there is no condensation and the temperature decreases, a process called gas cooling (Staub, 2004).

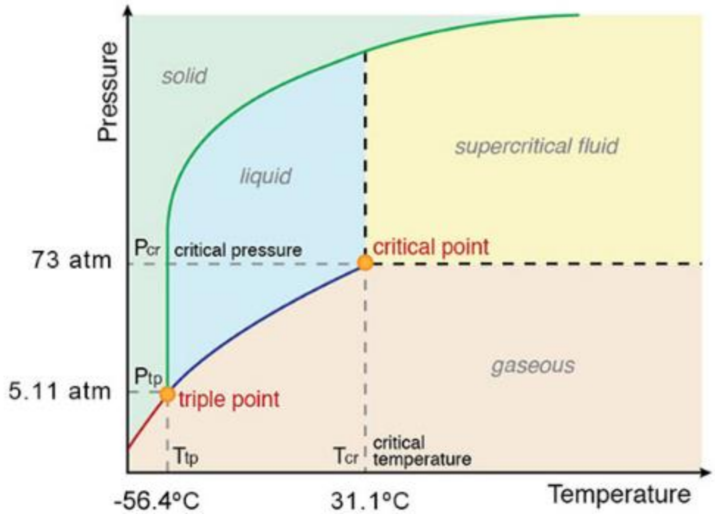

Figure 9. Phase diagram of CO_2 showing critical point at a temperature and pressure above and 31°C. 73 atm (Annenberg, 2018).

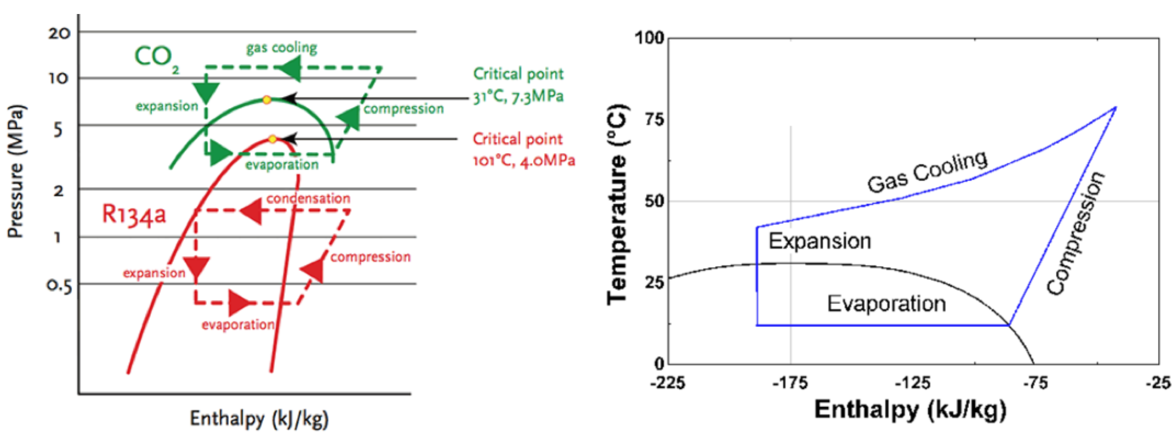

Figure 10. Pressure – Enthalpy (Left) & Temperature – Enthalpy (Right) diagrams for a R744 supercritical cycle where heat is absorbed at constant temperature and subcritical pressure and the heat is rejected at gliding temperature and supercritical pressure (Cibse Journal, 2012).

The efficiency of conventional water heaters is expressed as the energy factor (EF). It represents the efficiency of the heating elements and the storage tank thermal losses during a 24-hour test procedure. The energy factor is the ratio of energy output over input during laboratory testing conditions (DOE, 2018). The EF is used to be able to compare different models at the same input and working parameters. The efficiency of a HPWH will vary depending on different factors, such as the inlet water temperature, the temperature of the storage tank, the inlet air temperature, and the set point temperature. For real world conditions, the efficiency is described in terms of coefficient of performance (COP) (Cengel, 2008).

The Coefficient of Performance (COP) is the ratio of thermal energy delivered by the HPWH to the electrical energy used to produce it:

$$COP = \frac{Desired\ Output}{Required\ Input} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

Where:

$$q_H: magnitude\ of\ heat\ rejected\ to\ sink\ (Desired\ Output)[kJ/kgK]$$

$$w_{net,in}: net\ required\ work\ input\ (Required\ Input)\ [kJ/kgK]$$

$$h: specific\ enthalpy\ \ [kJ/kg]$$

The COP of the water heater can also be calculated by (Ullah & Healy, 2016):

$$COP = \frac{m * C_p * (T_{HPWH,out} - T_{HPWH,in})}{E_{HPWH}}$$

Where:

$$m: mass\ of\ hot\ water\ delivered\ [kg]$$

C_p: $specific\ heat\ of\ water\ [kJ/kgK]$

$T_{HPWH,out}$: $outlet\ water\ temperature\ of\ the\ HPWH$

$T_{HPWH,in}$: $inlet\ water\ temperature\ of\ the\ HPWH$

E_{HPWH}: $input\ electricity\ to\ of\ HPWH$

The Sanden CO_2 model uses R744 as the working fluid. The Sanden Model No. GS3-45HPA-US performance and specifications for two storage tank sizes are shown in Table 1. The Sanden model is a split system (Figure 11), meaning that the heat pump unit and the water storage tank are two different components. The heat pump unit can be placed where it can absorb heat from an optimal temperature area while the tank can be insulated to minimize losses.

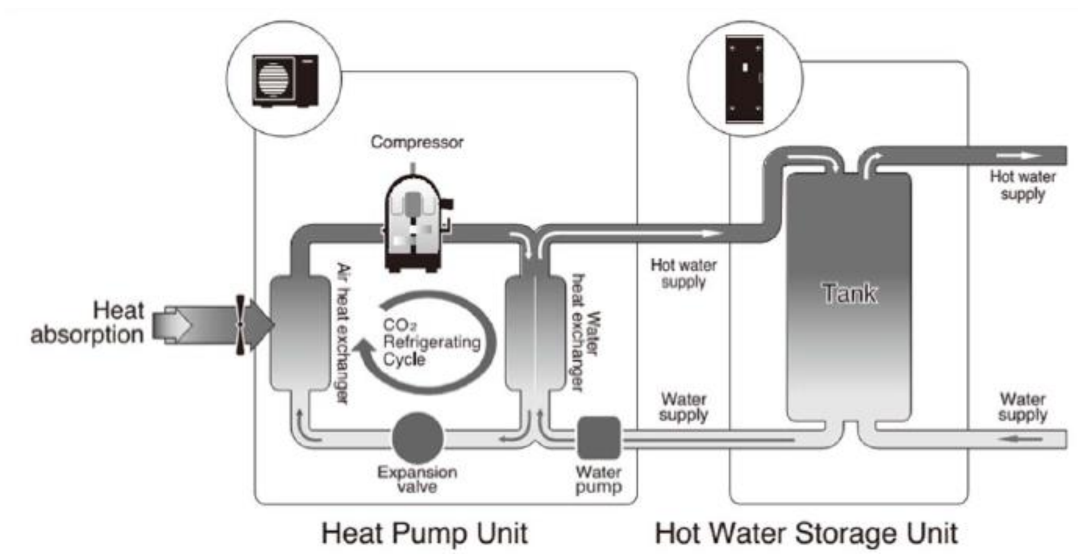

Figure 11. Schematic of Sanden Heat Pump Water Heater Split System. (Sanden, 2018)

The Sanden CO_2 heat pump refrigerant operates between the pressure range of 600 psi and 1600 psi (Sanden SANCO$_2$, 2017). The compressor discharge pressure varies from 1150 to 1650 psia and the discharge temperature is less than 230°F (Nawaz & Shen, 2017). The system can perform at a COP of 5.0 and the heat pump work input power is 4.5 kW. A thermodynamic process of the refrigerant state is shown in the next section. The process follows the states shown in the temperature – entropy diagram included in Figure 8.

Table 1. Sanden HPWH performance and Specifications (Sanden, 2018).

Performance	**43-gal system**	**83-gal system**
Energy Factor	3.09	3.84
First Hour Rating	71 gal	101 gal

Specifications	**Specifications**
Set Point Temperature	130˚F – 175˚F
Ambient Air Operating Conditions	-20˚F - +110˚F
Heat Pump Capacity	4.5 kW
Heat Pump COP	5.0
Refrigerant Type	R744 (CO_2)
Breaker Size	15 Amps

At State 1, the inlet pressure of the compressor is 4 Mpa and the working fluid is a superheated vapor. Assuming an operating point that is 5˚C from the saturation temperature, the enthalpy and entropy at State 1 is → $h_1 = 436.55\ kJ/kg\ \&\ s_1 = 1.8477\ kJ/kgK.$

At State 2s, the outlet pressure of the compressor is 11 Mpa, the temperature is between 100˚C and 110 ˚C, and the refrigerant is a superheated vapor. The enthalpy at State 2s is→ $h_{2s} = 495.90\ kJ/kg$ (NIST, 2018).

The Sanden HPWH has an inverter compressor type also called a variable frequency drive (VFD) compressor. This type of inverter compressor can control pumps and other motors' frequency reducing power consumption and providing higher efficiency (U.S. DOE, 2012). Assuming an isentropic compressor efficiency of 0.95, the mass flow rate of the refrigerant is $\dot{m} = 0.072\ kg/sec$.

$$\dot{W}_{net,in} = (\dot{m})(h_2 - h_1) = \frac{(\dot{m})(h_{2s} - h_1)}{n_{isentropic}}$$

$$(\dot{m}) = \frac{\dot{W}_{net,in} * n_{isentropic}}{(h_{2s} - h_1)} = 0.072\ kg/sec$$

The actual enthalpy at compressor exit can be estimated by:

$$h_{2a} = h_1 + \frac{h_{2s} - h_1}{n_{isentropic}} = 499.02\ kJ/kg$$

At State 3, the enthalpy can be calculated using the COP. The pressure at the condenser outlet is less than the inlet pressure.

$$h_3 = h_4 = h_2 - \frac{q_H}{w_{net,in}}(h_2 - h_1) = 184.67\ kJ/kg$$

The calculated enthalpies for the optimal heat pump performance will vary, and the COP of the HPWH will vary with changing hot water usage patterns and conditions.

The rate of electricity consumption of a heat pump water heater (HPWH) during operating conditions depends mostly on the hot water use patterns. Other factors affecting the rate of electricity consumption are the temperature of the air entering the evaporator, the temperature of the air around the tank, the inlet water temperature, and the set point temperature of the tank (NEEA, 2013).

One important constraint that limit the possibilities of HPWHs for achieving gains are outside temperatures. Air source heat pump water heaters are less efficient in cold climates because they need to extract heat from the surrounding air. Carbon dioxide (CO_2) refrigerant can achieve higher efficiency in colder climates and can generate higher water output temperatures (Sullivan, 2017). The Sanden CO_2 HPWH model lacks electrical resistance elements and might not respond in lower ambient temperatures as fast as an electrical water heater model.

2.5- Domestic Hot Water Use Profiles

Having knowledge and a better understanding of the DHW demand profiles can also allow for the design of control systems based on consumption patterns (Bertrand, MAstrucci, Schler, Aggoune, & Marchal, 2016). DHW use predictions and control techniques could enable HPWHs to supply energy balancing services by means of demand side management strategies (Gelazanskas & Gamage, 2015).

The consumption patterns for domestic hot water in building energy modeling are usually identical for each day of the year, neglecting the influence of climate conditions or other influential parameters such as the day of the week and season. Research has been done to obtain more realistic draw profiles based on probability methods for the estimation of water extraction events occurrence and duration (Fuentes, Arce, & Salom, 2018). A detailed characterization of DHW use profiles can also allow for a more reliable estimation of the energy consumed in the residential building sector.

The California Building Energy Code Compliance (CBECC) and the California Simulation Engine (CSE) draw profiles are based on a data set of measured draws from more than 700 California single family homes (Kruis, Wilcox, Luts, & Barnaby, 2017). Rather than estimate the draw profiles from statistical output, the approach is to measure draw profiles directly. The data were collected by measuring water using meters and recording the water flow volumes every 10 seconds over a period of two weeks. A pattern recognition algorithm assigned each draw to a specific end use. Five end uses are hot water related: showers, faucets, bathtubs, clothes washer, and dishwashers. This data set does not measure seasonal variations in water use. If occupants were to take longer showers in the winter or do more loads of laundry in the summer would not be characterized in the model. The model assumes that water use at the fixture varies by day, but on average is the same year-round.

More traditional approaches rely on estimating the water heating energy by time of the day by following an average daily profile on an hourly basis (Figure 12). This form of profile does not represent the characteristics of actual hot water draws that affect water heating energy because they represent the average (which never actually happens). Actual hot water draws tend to be short duration with high volume. These types of events can cause water heaters to operate less efficiently. However, short duration and high-volume (Figure 13) events can cause water heaters to operate in recovery mode making them less efficient. In general, domestic hot water demand ramps in the morning hours from 5:00 to 8:00 am and again in the afternoon during 5:00 to 8:00 pm (Figure 14).

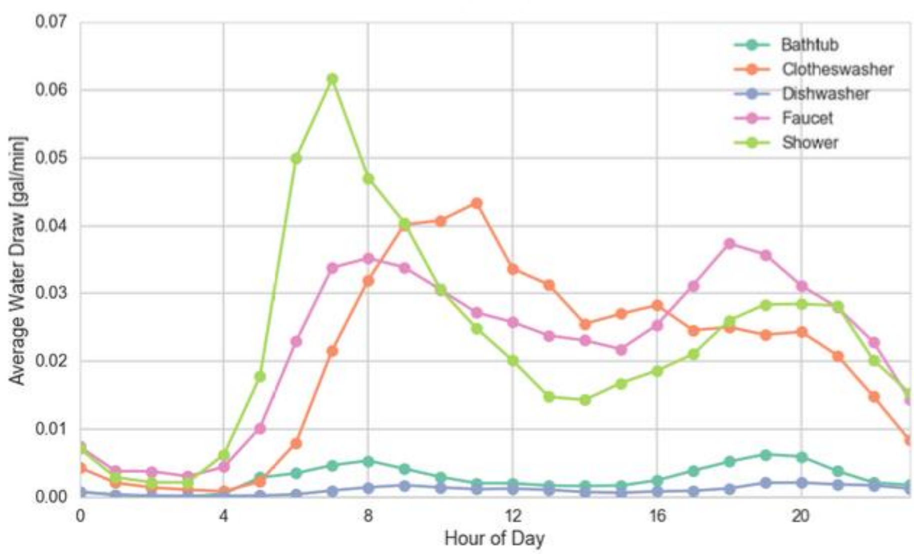

Figure 12. Average hourly water draw profile (Kruis, Wilcox, Luts, & Barnaby, 2017).

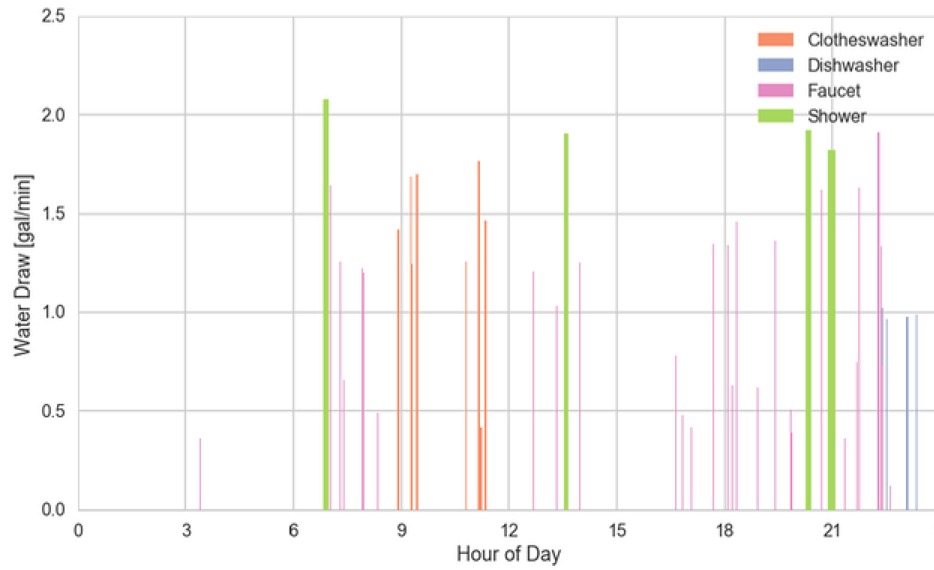

Figure 13. Real hot water draw profile (Kruis, Wilcox, Luts, & Barnaby, 2017).

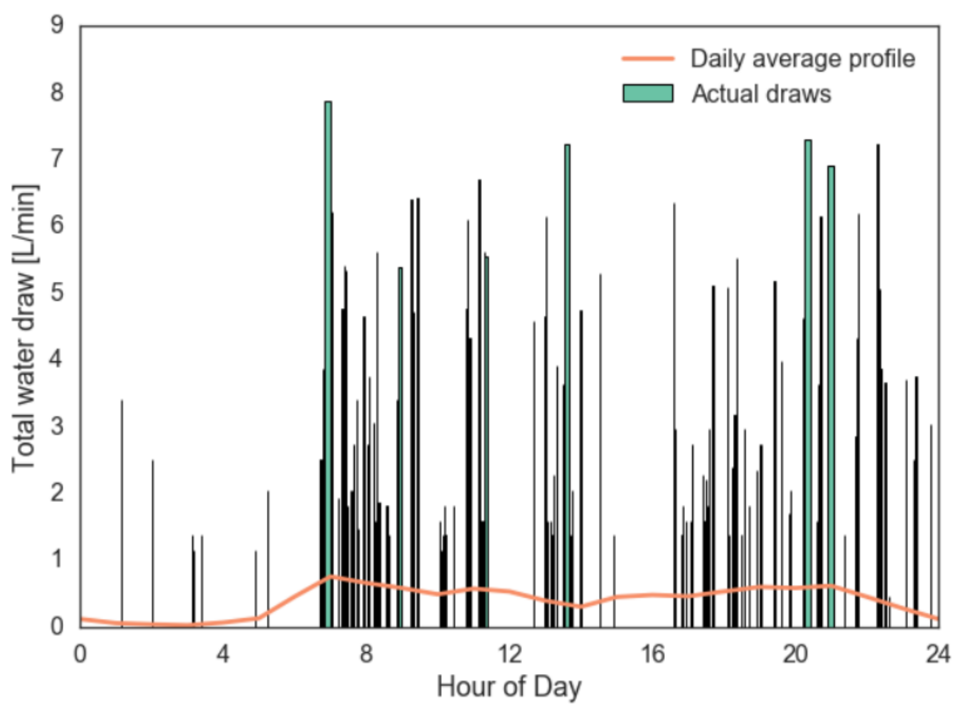

Figure 14. Comparison between average daily profile and actual draws (Kruis, Wilcox, Luts, & Barnaby, 2017).

2.6- California Building Climate Zones

There are 16 California Building Climate Zones (Figure 15) that each represent a geographic area and an energy budget for design standard. The climate zones contain summarized weather data for a reference city in each zone. The weather information can be used to develop strategies for appropriate passive design to each climate. Each zone has unique climatic conditions which dictate minimum efficiency requirements for that specific zone. For example, the required insulation, fenestration type or number of heating or cooling degree days (CEC, 2019).

Six climate zones represent 51% of the state's households, including San Francisco (CZ3), San Jose (CZ4), Sacramento (CZ12), Coastal Los Angeles (CZ6), Downtown Los Angeles (CZ9), and Riverside (CZ10). These regions cover most of the growing population centers of the state. Another 36% of the state's households are found in similar climate zones. The remaining 13% of the households are in northern, mountainous, or desert climates.

The largest building climate zone by area is Climate Zone 16 with a total area of 14,015,040 hectares. It has summer temperature range of 34 °F and an average altitude of 4108 ft. Climate Zone 16 is a high mountainous and semiarid region above 5000 ft. in elevation, and it covers the area from the Oregon Border to San Bernardino County. The climate is mostly cold but seasonal changes are well defined. The rest of the climate zones information is shown in Table 2 and Figure 15 below.

Table 2. California Building Climate Zones and other characteristics (CEC, 2006).

CZ	Area [Ha]	Summer Temperature Range [F]	Record High Temperature [F]	Record Low Temperature [F]	Reference City	Latitude	Longitude	Elevation [ft]
1	915246	15	85	21	Eureka	41.3 N	124.28 W	43
2	2032928	29	113	14	Napa	38.28 N	122.27 W	60
3	825862	29	113	14	Oakland	37.75 N	122.2 W	10
4	1853982	23	109	19	San Jose	37.35 N	121.9 W	70
5	795863	22	108	20	Santa Maria	34.93 N	120.42 W	230
6	254714	15	110	27	LA (LAX)	33.93 N	118.4 W	110
7	185586	14	111	29	San Diego	32.72 N	117.17 W	10
8	212852	15	111	25	Long Beach	33.82 N	118.15 W	30
9	421022	19	110	28	LA (CC)	34.05 N	118.23 W	270
10	817923	32	116	19	Riverside	33.95 N	117.38 W	840
11	2366961	32	119	20	Red Bluff	40.09 N	122.15 W	342
12	3091274	35	114	19	Stockton	37.54 N	121.15 W	22
13	3304821	34	111	19	Fresno	36.46 N	119.43 W	328
14	6864426	30	116	3	Barstow	35 N	116.47 W	1927
15	3017810	18	122	2	Brawley	32.95 N	115.55 W	0
16	14015040	34	109	-7	Bishop	32.22 N	118.22 W	4108

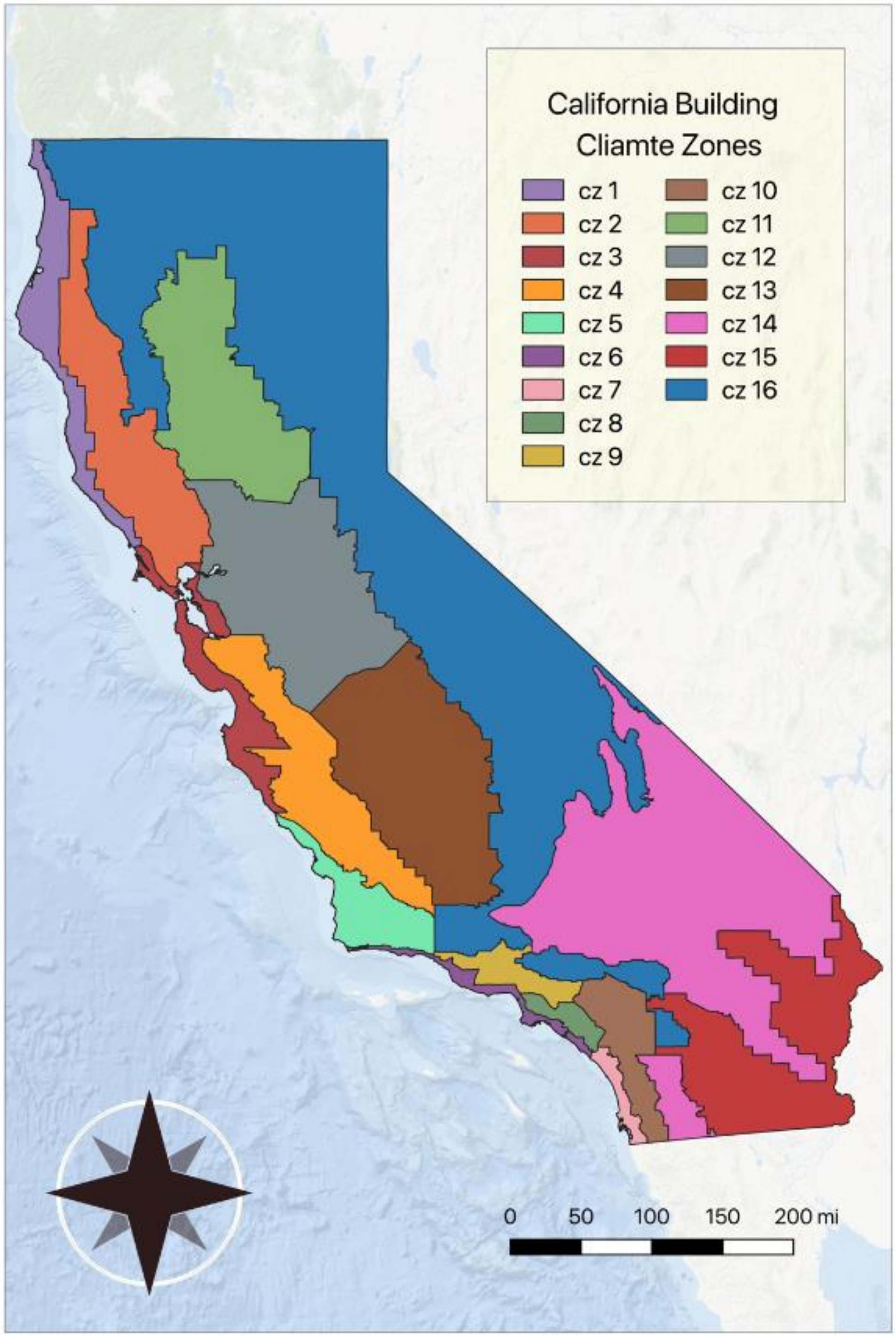

Figure 15. California Building Climate Zones represent a geographical area for which an energy budget is established. An energy budget is the maximum amount of energy that a building can be designed to consume per year (CEC, 2017).

2.7- Demand Response and HPWHs

While there has been research on the characteristics of electrical water heaters, there is not authoritative information on the performance and characteristics of HPWHs for demand response. Emerging evidence suggest key differences between HPWH and ERWH, and the capabilities of these systems.

Conventional electric water heaters maintain a set tank temperature by heating the water instantaneously following hot water draws (Figure 16). Programmable water heaters can preheat water and allow the temperature to drift down to a minimum temperature without reheating (Figure 17).

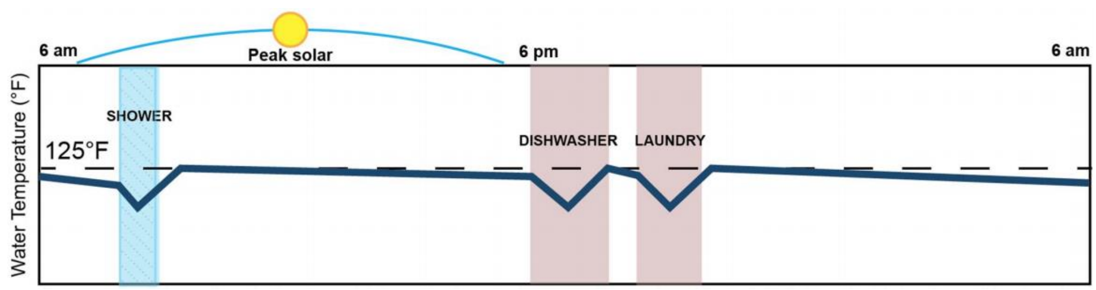

Figure 16. Constant set point temperature. The downward slope in the figure represents tank losses. (O'Shaughnessy, Cutler, Ardani, & Margolis, 2018)

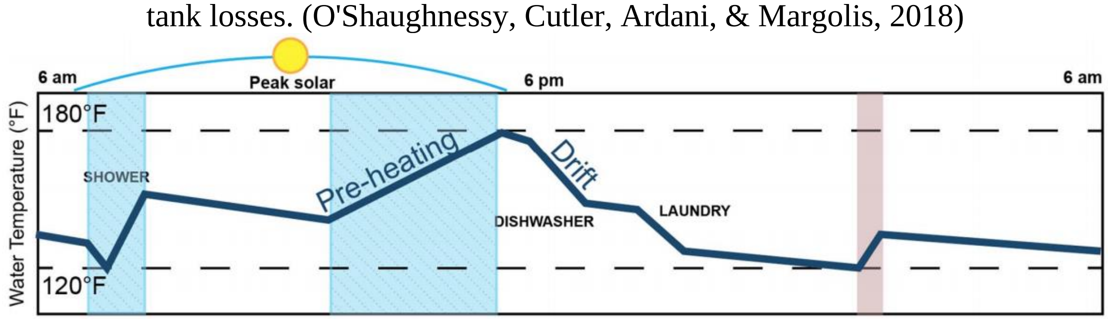

Figure 17. A smart DHW controls when the electric unit in the DHW is engaged to heat water. The water heater preheats the water to a high temperature and then drifts down until the following water draw. (O'Shaughnessy, Cutler, Ardani, & Margolis, 2018)

Load control technologies can reshape load profiles to optimize energy use. The temporal mismatch between solar photovoltaic systems' output and residential electricity demand is one of the primary challenges to PV integration. PV output often exceeds residential electric loads during the day but falls short of demand in the late afternoon and evening when residential loads tend to increase (O'Shaughnessy, Cutler, Ardani, & Margolis, 2018).

Generally, the thermal energy going into and out of the tanks is similar for a HPWH and standard ERWHs, but the amount of electrical energy input is lower in the HPWHs due to their greater efficiency. As a result, the effective electric energy storage capability from a power grid perspective is less for HPWHs (NEEA, 2014). However, HPWHs while less flexible than electric resistance water heaters, still have demand respond value.

In 2018, a pilot program in Connecticut from the local utility, United Illuminated (UI) and HPWH maker Rheem launched a new offer to its customers. The utility offered a free HPWH if the customer agreed to allow the utility to control it during key hours, primarily winter morning and evenings. These are the hours when grid operators see rising energy demand for heating that coincide with dropping generation supply from power plants being forced offline by the cold weather. Over the course of the winter of 2018, UI successfully predicted, scheduled, and dispatched a series of demand response calls to the Rheem HPWHs that involved turning them off until the water reached a minimum temperature threshold during periods of demand response events (John, 2019).

The Northwest Energy Efficiency Alliance (NEEA) conducted a study on HPWH demand response capabilities over a two-month period in the Cowlitz County Public Utility District (CPUD) service territory. Demand response capabilities were tested by reducing the storage tank temperature during peak hours for the utility, 2 hours in the morning and 3 hours in the evening. The ability to store energy was tested by raising tank temperature during night time hours to “charge” the tank in anticipation of morning hot water usage (NEEA, 2014). The project tested the ability to both decrease and increase water heater electric loads in response to a communication signal, all without affecting the quality of water heating as perceived by the end user.

With the increased communication and control capabilities in the smart grid, it is now possible to dynamically modulate loads to match supply more conveniently and cost effectively (NEEA, 2014). Peak curtailment or peak load reduction drops noncritical loads for a period of 4-6 hours during the time when power use is the highest and the strain on the grid is the greatest. This can decrease the use of inefficient fossil fuel peaking plants. As increasing amounts of wind and solar are introduced to the grid, the need for balancing to respond to fluctuations in wind speed or insolation will be needed. The main idea is that the customer will never notice the water temperature has changed as the energy usage is shifted to a different time. Critical to this method are tempering valves installed on the tank output that mix cold water with “overheated” water from the tank, so that the tank temperatures up to 180ºF could be achieved while delivering water to customers at a safe temperature (no greater than 130 ºF).

The amount of energy stored in a water heater is directly proportional to the tank size and temperature. The Natural Resources Defense Council (NRDC) conducted a load shifting study that showed that the optimal range for storing extra energy in HPWHs is a set point of 130 to 140 °F, and higher for electric resistance tanks (NRDC, 2018). This is a seemingly small increase in temperature over 125 °F, but it balances increased energy storage against reduced compressor operating efficiency and increased heat loss. Higher temperatures may be warranted on occasion, during extreme grid events, but for day to day load shifting the modest increase proved most useful. In a nominal 50-gallon HPWH tank, elevating the temperature from 125 °F to 145 °F increases the stored energy by roughly 25% or the equivalent of 5.5 kBtu (1.6 kWh). Since the HPWH operates with a COP greater than one, the amount of electricity needed to create that extra stored water energy is the increased in stored energy divided by the COP.

The water temperature at the point of use needs to be lower than the tank temperature. Including a mixing valve (Figure 18) in the water heaters or adding one at the time of installation allows the tank temperature to be increased while still limiting the domestic hot water supply. By choosing when to increase the water tank temperature, e.g., mid-day when excess solar power exists, this energy can be used later when hot water is needed without the tank needing to heat as much as it otherwise would, because hot water energy was already put in the tank. In maximizing performance of water heater energy storage in a demand response program, a mixing valve is critical. For a given tank size it allows the tank to store more energy than during normal operation (NRDC, 2018).

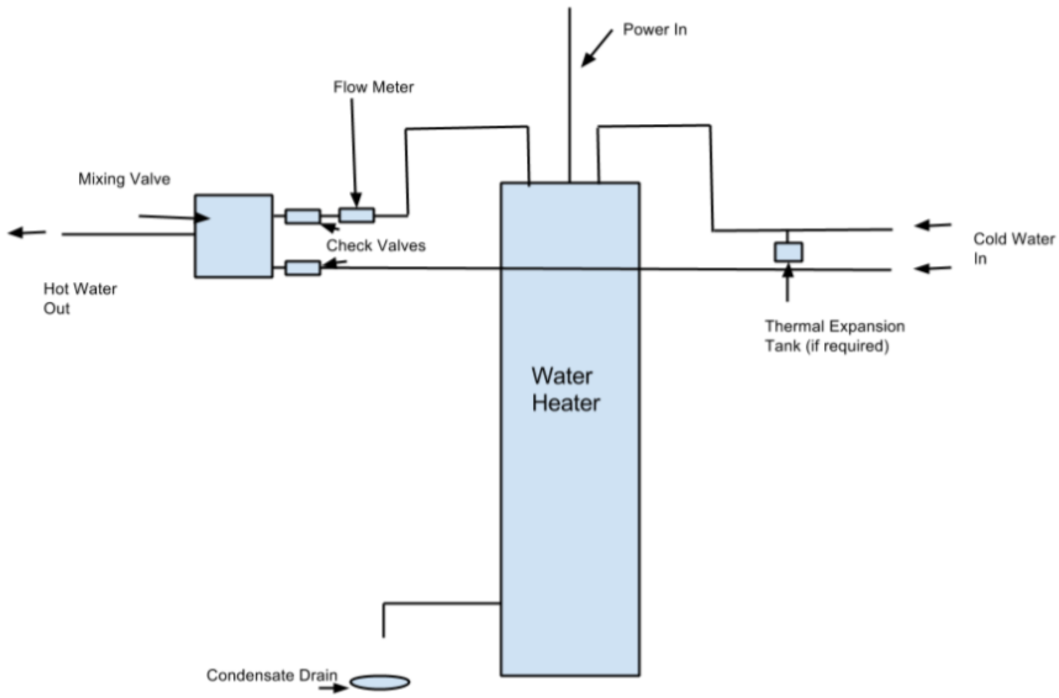

Figure 18. Heat Pump Water Heater with mixing valve and flow meter (ECOFYS, 2014).

2.8- Water Heater Cost

The largest market barrier for energy efficient water heaters for residential buildings is the high capital cost (Hopkins, Takahashi, Glick, & Whited, 2018). The capital cost of water heaters consists of two major components: the equipment cost (Table 3) and the installation cost (Table 4 & Table 5). All water heaters have some seasonal variations in energy use, as hot water use change with mains water temperature, but some technologies including HPWHs, are more sensitive to seasonal changes. HPWHs have an efficiency that is greater than typical electric water heaters, but questions remain about their actual performance and energy savings potential.

Table 3. Capital and operation cost of different type of water heaters (Smarter House, 2019).

Water heater type	Storage volume (gal)	Efficiency (UEF)	Capital Cost[1]	Annual energy cost[2]
Conventional gas storage	40	0.60	$850	$350
High efficiency gas storage	40	0.65	$1025	$323
Minimum efficiency electric storage	50	0.90	$750	$463
High efficiency electric storage	50	0.95	$820	$439
Electric heat pump water heater	50	2.20	$1660	$190

Notes:
1. Costs are rough estimates, including installation, based on internal and other surveys.
2. Based on hot water needs for typical family of four and energy cost of 9.5¢/kWh for electricity and $1.40/therm of gas.

Table 4. Equipment and net installed cost for different water heating technologies (DOE, 2010).

Water heater type	Equipment Cost	New construction net installed cost	Retrofit net installed cost
Gas Storage	$450	$1329	$968
Electric Storage	$283	$467	$598
HPWH	$1169	$1414	$1622

Table 5. Life Cycle cost for 13-year operation of different types of water heaters (DMME, 2008).

Water heater type	Efficiency	Cost[1]	Yearly energy cost[2]	Life (years)	Cost over 13 years[3]
Conventional gas storage	55%	$425	$163	13	$2544
High efficiency gas storage	62%	$500	$145	13	$2385
Oil fired free standing	55%	$1100	$228	8	$4751
Conventional electric storage	90%	$425	$390	13	$5495
High eff electric storage	94%	$500	$374	13	$5362
Demand gas	70%	$650	$140	20	$2243
Demand electric	100%	$600	$400	20	$5590
Electric heat pump	220%	$1200	$160	13	$3280
Indirect water heater with efficient gas or oil boiler	75%	$700	$150	30	$2253

Notes:

1. Approximate cost of appliance plus installation
2. Energy cost based on hot water needs for typical family of four and energy cost of 8¢/kWh for electricity, 60¢/therm of gas, $1.00/gallon for oil.
3. Future operation costs are neither discounted nor adjusted for inflation. Source: American Council for an Energy Efficient Economy, Consumer guide to Home Energy Saving.

The total life cycle cost of operating a water heater consists of the initial capital cost, installation cost, any upgrade cost, annual maintenance cost, annual fuel or energy cost. A recent study (Raghavan & Wei, 2017) shows that the capital and maintenance cost of HPWHs in three different adoption years is higher than natural gas and electrical resistance heaters. The solid color bars are the annualized cost for capital, installation, and maintenance cost. However, the operation cost of HPWHs is significantly less than an electric resistance heater and similar to a natural gas heater (Figure 19). The shaded section is the average annual energy cost. The hatched tip of each bar is the average annual social cost of carbon cost assuming a carbon tax of $57.50 per ton of emission is levied.

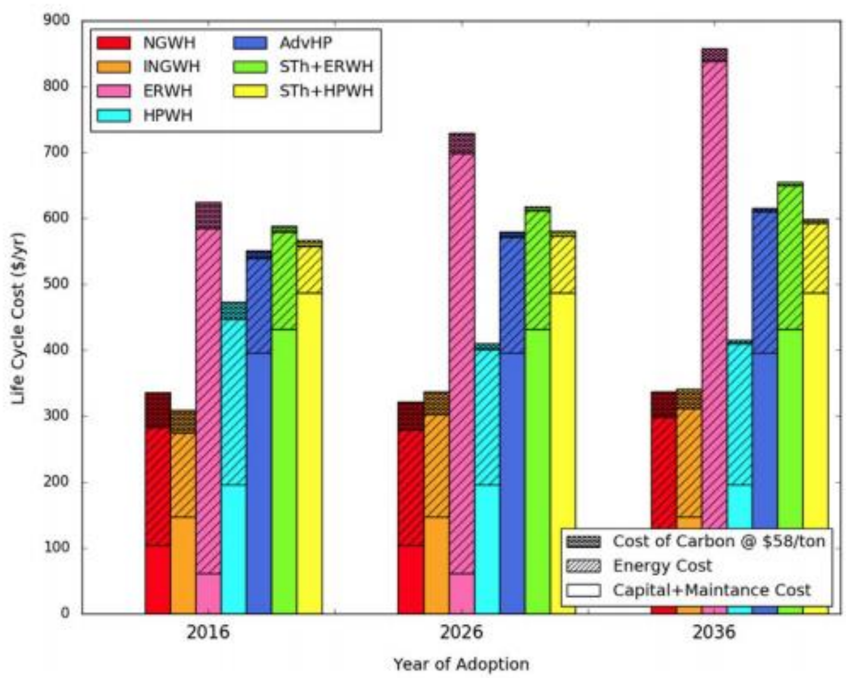

Figure 19. Life cycle cost of water heater technologies in three adoption years. Efficiencies and refrigerant GWPs improve with each adoption year (Raghavan & Wei, 2017).

The current retail price of natural gas is roughly 4.5 times cheaper than electricity at $0.04 per kWh (or $1.138 per therm) while the average retail electricity price in the residential sector is $0.175 per kWh (US EIA, 2018).

The current efficiency standards of the most prevalent storage NGWH is 0.675 (CEC, 2016). A more energy efficient natural gas option is an instantaneous or tank less water heater with an efficiency factor of 0.82 and above. Instantaneous water heaters have a higher installed cost due to the need to deliver higher instantaneous energy than storage NGWH.

Among electric water heaters, electrical resistance (ERWH) have the largest market share. The current energy factor standards of electric water heaters are 0.96 for ERWH and 2.0 for HPWH. Sanden has begun marketing SANCO_2 in North America, a heat pump with carbon dioxide as a refrigerant and a higher COP. Due to natural gas fuel prices NGWH remain the cheapest option for consumers on a lifecycle basis.

The annual emissions of a water heater will depend on the amount of hot water consumption, the efficiency of the appliance, GWP of the refrigerant and leakage assumptions, and the carbon intensity of the fuel source in that year. For HPWHs the solid color in the bottom of the bars represents emissions from fuel source and the top hatched part represents the emissions due to leakage (Figure 20). The figure shows a comparison of emissions and life cycle costs of the five technologies for three different installation years at varying energy factors.

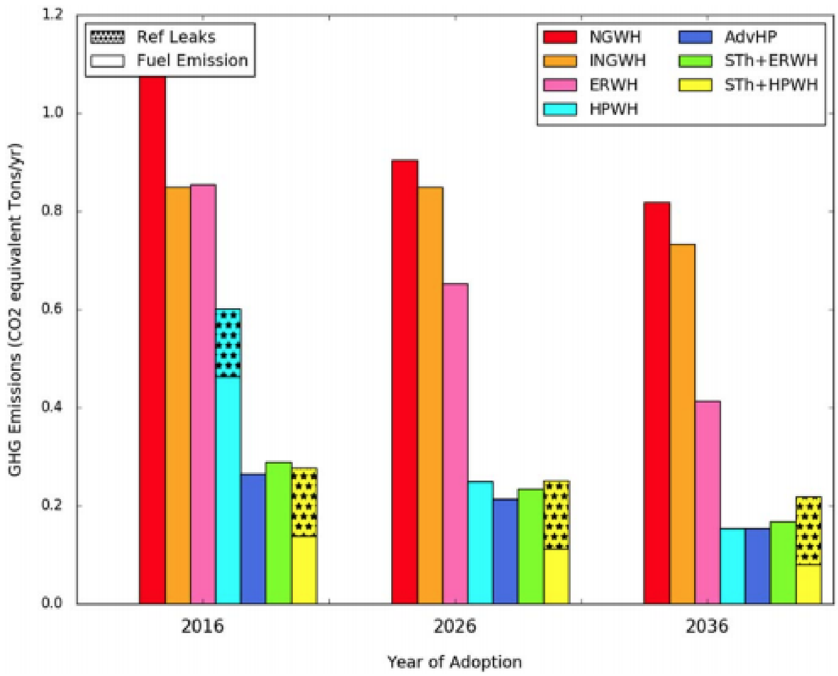

Figure 20. Average annual emissions from source fuel and refrigerant leakage in three adoption years. Efficiencies and refrigerant GWPs improve with time. (Raghavan & Wei, 2017)

MATERIALS AND METHODS

The energy demand for domestic hot water is estimated using building energy simulation software. The California Building Energy for Code Compliance for residential buildings (CBECC-Res) and the California Simulation Engine (CSE) were used to develop estimates of hourly energy demand. The electrification of domestic hot water (DHW) will be explored by analyzing the amount of natural gas and electricity consumed in California residential buildings by climate zone. The yearly electricity and natural gas consumption for water heating for typical single-family and a multifamily house are used to estimate the cost and GHG emissions.

The fuel switch analysis is conducted by computing the amount of natural gas reduction and the equivalent increase in required electric load for the operation of HPWHs in California buildings. The exercise allows calculation of the possible savings on future building developments for energy design and efficiency.

3.1- Building Energy Modeling – CBECC-Res & CSE

The electricity consumption and the performance of the system are simulated using open source software, with the hourly data are obtained from the California Simulation Engine (CSE) and the California Building Energy Code Compliance for Residential buildings (CBECC-Res) software. Both are building simulation applications developed to support the California Title 24 residential energy standards for state code compliance (Barnaby & Wilcox, 2013). The California Title 24 Standards specify minimum performance levels for major building components such as the insulation factor for walls and fenestration and HVAC equipment efficiency. A residence complies with the standards if its calculated energy use is not greater than that of a reference house having the prescribed characteristics. The CBECC-Res is developed by the CEC for demonstrating compliance for low-rise residential standards, which include single-family dwellings, duplexes and townhomes, as well as multifamily buildings with up to three stories. The CBECC-Res software is public domain. It is certified by the CEC to conform to the Residential Alternative Calculation Method (ACM) Reference Manual, which establishes the rules for how the proposed design energy use is defined (CEC, 2019).

The CSE is the result of two previous projects. First, in the 1990s the CEC developed a program called CNE that was intended for code compliance applications, but it was never deployed. Second, during 2005-2010 updated residential models were developed to support the 2008 California Title 24 Residential Standards. These models were implemented as prototypes, and some were made available publicly. The CSE is the result of merging the prototype implementations into the CNE framework. The CSE operates in batch mode under control of text input files and writes results to the text or binary files (Barnaby, Wilcox, & Niles, 2013).

CBECC-res is used to model all components that affect the energy performance of a building as required for complying with the 2019 building energy efficiency standards. The CBECC-res application software works by using a simple graphical user interface (GUI) that allows the user to simulate the envelope and construction of a building. The basic input parameters for building energy modeling are:

- Climate zone, front orientation, fuel type, PV system details
- Conditioned floor area and average ceiling height
- Attic/roof details, roof pitch, roofing material, solar reflectance and emittance
- Ceilings below attic and vaulted ceiling R values
- Wall areas, orientation, and construction details
- Window and skylight areas, orientation, U factor, solar heat gain coefficient
- Building overhang and side fin shading
- Mechanical heating and cooling equipment type and efficiency
- Distribution system location and construction details
- Method for providing mechanical ventilation
- Domestic water heating system details, type of hater heating equipment, fuel type, efficiency, distribution system details.

Why use the CSE as opposed to adapting existing public domain software such as DOE-2 or Energy Plus for California residential compliance applications? Some methods used in DOE-2 are not well suited to modeling the envelope and air leakage effects that dominate the residential performance. Energy plus lacks needed features and has many capabilities that are not needed which results in a large installation package. In contrast the CSE is very lightweight (the executable file ".exe" is less than 2 MB) and is practical to deploy in a compliance context. The CSE development is streamlined due to its small, dedicated code base that can be modified without worrying about implications for a wide user community (Barnaby, Wilcox, & Niles, 2013).

The annual hourly load for three different types of DHW systems (NGWH, ERWH, and HPWH) are simulated. The electrical and economic analysis requires the HPWHs periods of operation to balance with grid dynamics without altering end use behavior. The optimal DHW scheduling is explored by altering the DHW system in the CSE. An example of a schedule algorithm for operating a DHW system by overheating the storage tank to a set point temperature of 145 °F between 10:00 am until 1:00 pm and 125 °F for the remaining hours is shown below:

```
ALTER DHWSYS   "dhwsys-DHW Sys 1"
        wsTSetpoint = select($hour > 10 &&  $hour <= 13, 145, default 125)
```

3.2- Building Types and Climate Zones in California

California's population of 39 million resides in 13 million households. The department of finance (DOF) forecasts that population will grow to 50 million people by 2050 in approximately 16 million houses. Most households live in single-family dwellings; however, most new constructions are multifamily housing (DOF, 2019). Logistical barriers to electrification are lower for new construction than for retrofitting existing housing. It is easier to install HPWHs on new constructions, as opposed to retrofits which can be more expensive and require adjustments such as ducts, wiring, and placement. New construction is expected to represent about half of the building stock by 2050.

To enable energy analysis, it is necessary to identify a range of residential and non-residential building types among existing constructions (Table 6). Two building types are modeled, a one-story single-family home and a multifamily low-rise building complex. For each of the building types, a building simulation is performed across six California climate zones (

Table 7 & Figure 21). The climate zones were selected to represent a sample of the largest population centers in California. These climate zones are broadly representative of about 90% of the state's households. The remaining households in the state are largely rural.

Table 6. California building energy prototype (Calthorpe Analytics, 2016).

Residential	Non-Residential
• Single family detached, one story (~1,600 sq ft) • Large single family detached, one story (~2,100 sq ft) • Single family detached, two story (~2,700 sq ft) • Town home (~1,350 sq ft) • Multifamily low rise, garden style (8 units at ~870 sq ft each)	• High-rise multifamily residential • Restaurant (quick service, full service) • Retail (Strip mall, stand alone, large) • Hotel • Office (small, medium, large) • School (primary, secondary) • Warehouse • Retail • Medical office • Refrigerated warehouse • Convenience Store and gas station • Hospital • Parking Structure

Table 7. Percent of retrofits and new construction of residential buildings (as of 2020) assumed by climate zone and utility in the modeled study area (Mahone, Li, Subin, Sontag, & Mantegna, 2019).

CZ	City	Utility	Retrofit Single Family	Retrofit Low-rise Multifamily	New Construction Single Family	New Construction Low-rise Multifamily
CZ 3	San Francisco	PG&E	17 %	4 %	14 %	9 %
CZ 4	San Jose	PG&E	8 %	2 %	6 %	4 %
CZ 12	Sacramento	SMUD	7 %	2 %	6 %	4 %
CZ 6	Coastal LA	SCE	10 %	3 %	7 %	5 %
CZ 6	Coastal LA	LADWP	2 %	1 %	1 %	1 %
CZ 9	Downtown LA	SCE	12 %	3 %	8 %	5 %
CZ 9	Downtown LA	LADWP	13 %	3 %	9 %	6 %
CZ 10	Riverside	SCE	11 %	3 %	9 %	6 %

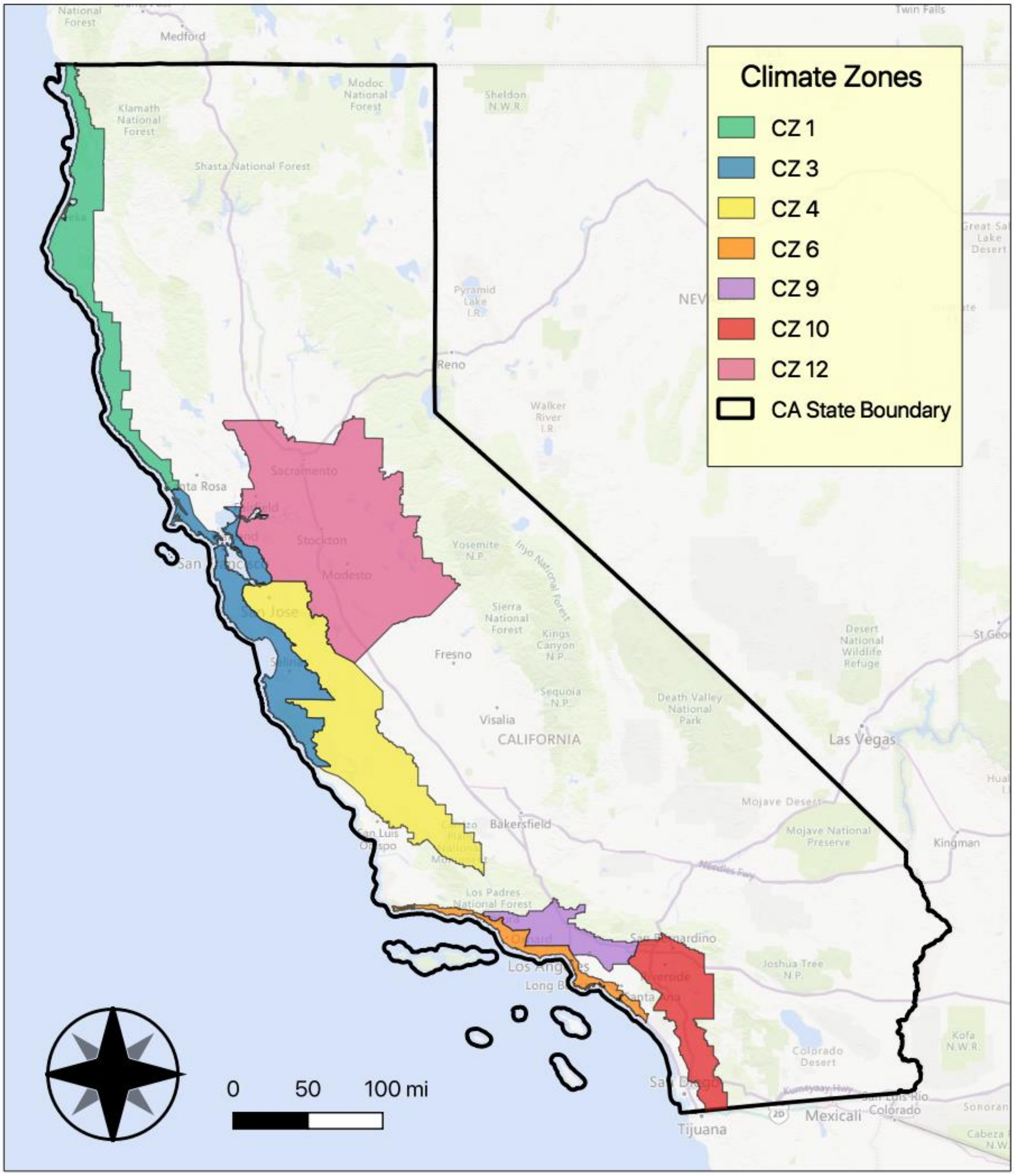

Figure 21. California climate zones selected for the building energy modeling simulation. (CEC, 2018)

3.3- Modeled Buildings in the CBECC-Residential Tool

The two modeled buildings in the CBEEC tool are one single and one multifamily residential building for each of the seven climate zones described in the previous section. The input parameters used for the building simulations are shown in Table 8.

The single-family building is a one story three-bedroom building with a combined floor area of 1,540 ft^2 and a total zone volume of 13,860 ft^3. The multifamily building is a two-story building with a total of eight dwelling units and twelve bedrooms. The combined floor area of the multifamily building is 6,960 ft^2, and it has a total zone volume of 27,840 ft^3. Each floor in the multifamily building has 4 units. The distribution of rooms is described in Table 9.

Table 8. Parameters and characteristics for modeled building types (CBECC-Res, 2019).

	Multifamily	**Single Family**
Dwelling Units	8	1
Stories	2	1
Bedrooms	12	3
Conditioned Floor Area (ft^2)	6,960	1,540
Total Conditioned Zone Window Area (ft^2)	1042	284.3
Window to Floor Area Ratio	0.15	0.185
Area-Weighted Fenestration U factor (Btuh/ft^2 °F)	0.3	0.3
Exterior Wall Area (ft^2)	4,984	969
Conditioned Zone Slab Floor Area (ft^2)	3,480	1,540
Zone Volume (ft^3)	27,840	13,860
Exposed Slab Floor Area (ft^2)	696	308
Envelope Infiltration (ACH @ 50 Pa)	7	5
Envelope Infiltration (CFM @ 50 Pa)	6,496	1,155

Table 9. Multifamily building dwelling unit distribution (CBECC-Res, 2019).

Floor	Description
First floor one bedroom	2 units, 1 Bedroom & 780 ft^2 per unit
First floor two bedroom	2 units, 2 Bedroom & 960 ft^2 per unit
Second floor one bedroom	2 units, 1 Bedroom & 780 ft^2 per unit
Second floor two bedroom	2 units, 2 Bedroom & 960 ft^2 per unit

The modeled water heater tanks for the single-family home and the multifamily residential complex are a 50-gallon tank and an 80-gallon tank, respectively. The HPWH model used for the energy simulation is a Rheem (model *PROPH50 T2 RH245*) NEEA rated with a uniform energy factor (UEF) of 3.55 and a first hour rating (FHR) of 67 gallons. The ERWH model used for building energy simulation is a generic electric resistance model with a UEF of 0.92 and a FHR of 60 gallons. The NGWH model used for the building energy simulation is a generic gas storage model with a UEF of 0.56 and a FHR of 80 gallons. A summary of the input parameters for the building energy simulations are shown in Table 10.

Table 10. Water heater input parameters for the single family and multifamily building energy simulations (CBECC-Res, 2019).

	Singe family	Multifamily
Storage tank volume	50 gal	80 gal
Uniform Energy Factor (HPWH)	3.55	3.55
First Hour Rating (HPWH)	67 gal	67 gal
Uniform Energy Factor (ERWH)	0.92	0.92
First Hour Rating (ERWH)	60 gal	60 gal
Uniform Energy Factor (NGWH)	0.56	0.56
First Hour Rating (NGWH)	80 gal	80 gal

The Uniform energy factor (UEF) is the DOE's newest measure of water heater overall efficiency. UEF ratings are determined by assigning water heaters into one of four different categories of hot water usage and then evaluating their performance based on that usage. These categories are called bins. A water heater is assigned a UEF within its bin based upon its first hour rating. A higher UEF means a water heater is more energy efficient and will cost less to operate compared to other water heaters in the same bin. A water heater's UEF can only be compared with other water heaters in the same bin. Based on the bin in which a water heater is categorized a predetermined amount of hot water usage is applied to that water heater to determine the annual cost of operation. The Energy Factor (EF) is an older measure of water heater overall efficiency that is being phased out due to new test methods for water heaters. The higher the EF value is, the more efficient the water heater.

First-hour rating (FHR) is an estimate of the maximum volume of hot water in gallons that a storage water heater can supply within an hour that begins with the water heater fully heated. The FHR is measured at 135 °F outlet temperature in the Energy Factor test method and at 125 °F outlet temperature in the Uniform Energy factor test method.

3.4- CPUC Net Short Emissions Intensities

Burning gas directly creates the same amount of emissions no matter when it is consumed. Emissions from electricity vary over the course of the day. They're higher in the evening during peak demand when power is supplied by fossil fuel power plants, and lower in the midday when demand is low and solar energy is abundant. Therefore, the GHG emissions associated with a HPWH depends on what time of the day it runs.

California's goal is to add renewable energy sources and make the power mix as clean as possible. With the excess of solar electricity during the middle of the day and the ramping of fossil fuel power plants in the afternoon some hours are cleaner than others. The California Public Utilities Commission (CPUC) has a new accounting methodology designed to provide insight on emissions associated with generation. The Clean Net Short (CNS) methodology allocates GHG emissions to each load serving entity (LSE) based on projected hourly electricity demand (CPUC, 2018). The method is demand or load based, in contrast to many GHG accounting frameworks that are source-based and based on annual averaging. The CPUC provides real time marginal GHG emissions factor for the North Path 15 (NP15) and South Path 15 (SP15) CAISO zones, at 5-minute intervals, in units of $kgCO_2/kWh$. Path 15 (Figure 22) is an 84-mile portion of the north-south power transmission corridor in California. It forms an important transmission interconnection with the hydroelectric plants to the north and the fossil fuel plants to the south.

Figure 22. CAISO NP15 and SP15 regional areas. (California ISO, 2020)

The marginal GHG emission rate for the north and south regions with respect to path-15 are shown in Figure 23 and Figure 24. The 5-minute data are summarized to represent an average day per month during a 24-hour period. The emission factor is lower during the times associated with solar generation, as shown in the highlighted yellow area in Figure 23 and Figure 24. The highlighted blue area shows the time when wind generation is higher.

Using high efficiency electric heat pumps instead of gas for residential water heating could cut greenhouse gas (GHG) emissions. It makes sense that using heating equipment that is far more efficient than conventional gas equipment, and powering it with California's increasingly clean electricity could dramatically reduce overall emissions. However, it's important to consider two additional factors, including the timing of electricity use and how much heat pumps operate in the less efficient resistance heating mode or time of use.

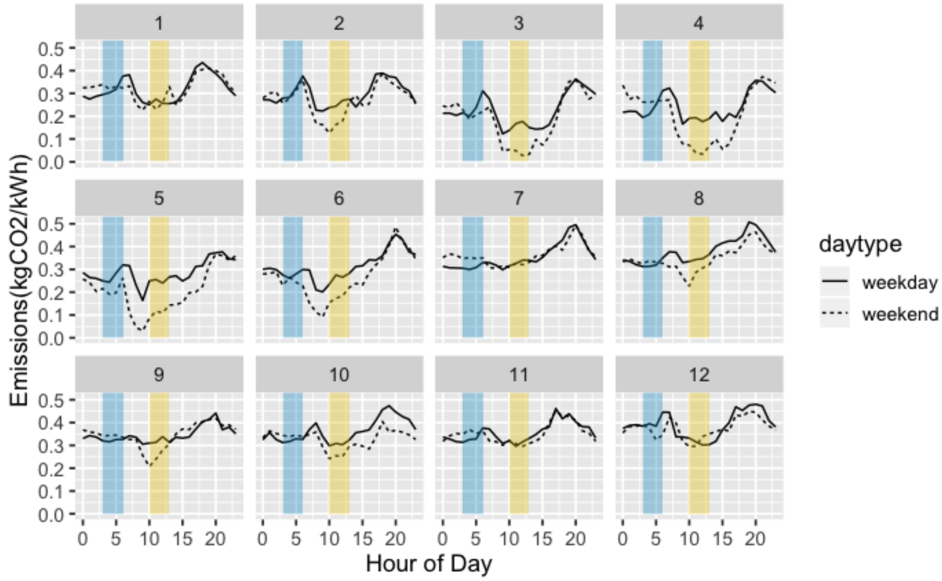

Figure 23. North Path 15 (NP15) GHG marginal emission rate. The yellow area shows the time when emissions are lower during high solar generation. The highlighted blue area shows the time when wind generation is higher during the day (CPUC, 2017).

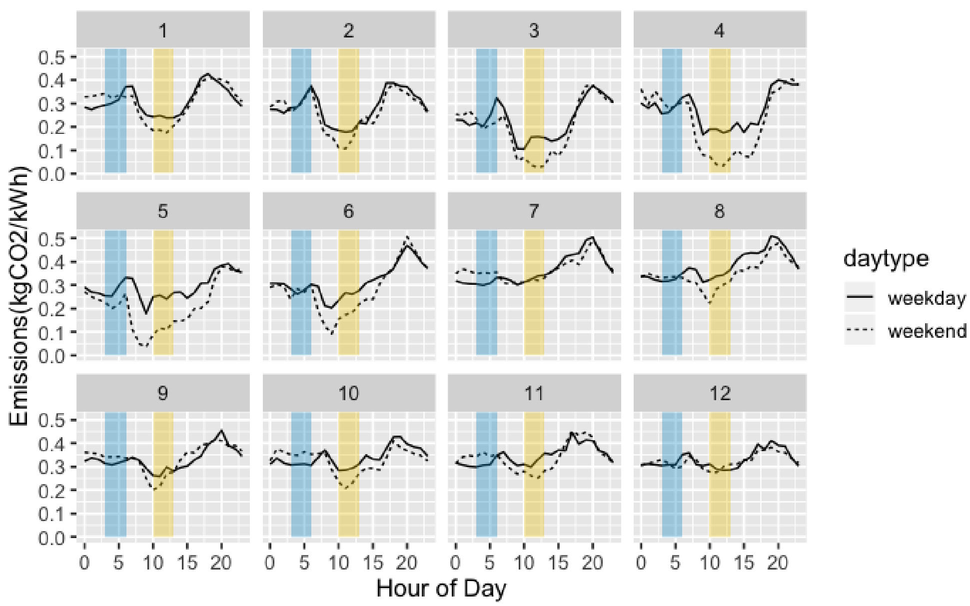

Figure 24. South Path 15 (SP15) GHG marginal emission rate. The yellow area shows the time when emissions are lower during high solar generation. The highlighted blue area shows the time when wind generation is higher during the day (CPUC, 2017).

3.5- Modeling Approach

The data presented in this thesis are obtained from building energy modeling (BEM) hourly simulations. The two residential buildings modeled represent the average multifamily and single-family constructions in California. The building model is the same for each climate zone simulation. The only variable that changes in the energy simulation is the water heating system.

Three different water heater systems are simulated, including a natural gas water heater (NGWH), an electrical resistance water heater (ERWH), and a hybrid heat pump water heater (HPWH). The base case results represent the standard load of the CSE model, assuming an average daily water draw profile associated with the use of the water heating system. The energy consumption data are used to estimate the annual cost of operation and the GHG emissions associated with the different water heater types in the simulation.

Sensitivity analyses are explored by changing the schedule of operation of the water heating system for the ERWH and the HPWH. After the base case scenarios are analyzed, the schedule of operation of the water heating system is altered in two different ways. The first alternative case consists of overheating the water tank to 145° Fahrenheit from 3 am to 6 am. These hours of operation are intended to match the high production hours of wind generation (Figure 25). The second alternative case consists of overheating the tank to 145° Fahrenheit from 10 am to 1 pm. These hours of operation match with the average daily solar peak production in California (Figure 25).

The idea behind shifting the operation schedule is to overheat the water heater tank during the hours when the electricity rates are low, when the marginal emission rates are low (Figure 23 & Figure 24), and/or when there is an excess of renewable power generation to avoid curtailment. For the base case and also the alternative load profiles, the cost is calculated to compare the operating cost to the base case scenario.

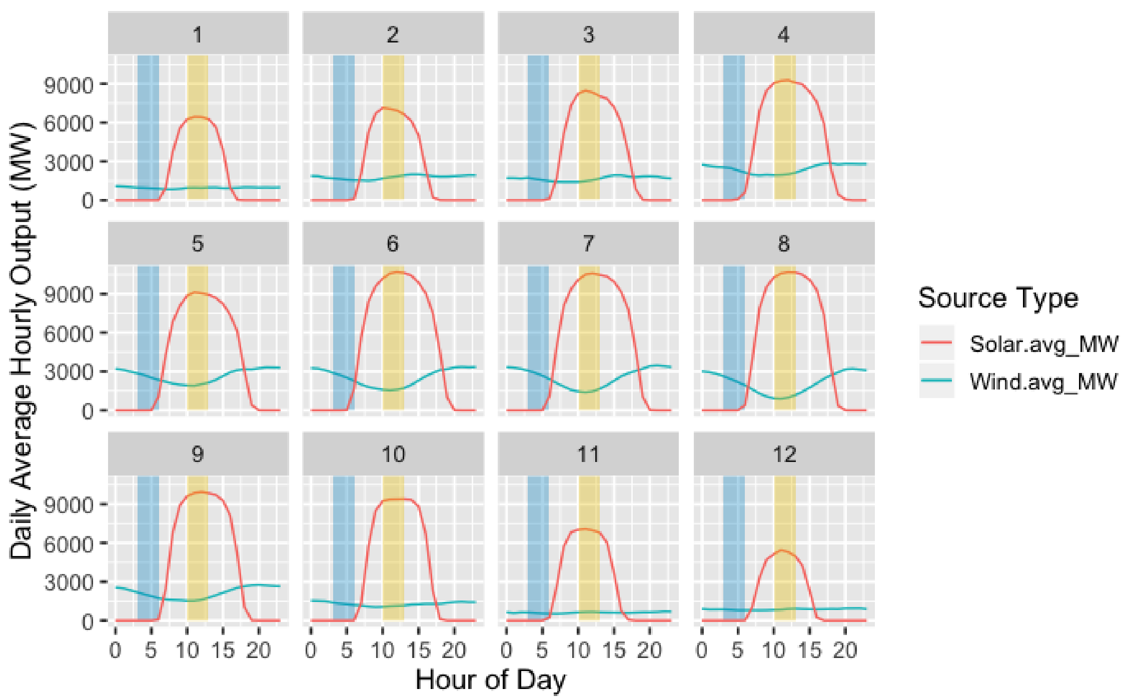

Figure 25. Average daily hourly output (MW) from wind and solar generation in California during 2019 (California ISO, 2020).

Thus, there are two different alternative simulation cases performed per water heating system. One is overheating the tank every day of the year during the periods from 3 am to 6 am hours and the other is overheating the tank during 10 am to 1 pm. However, it is impractical to overheat the water tank every day of the year. The decision of whether to overheat or not could be based on criterion such as days with low emissions and surplus energy from solar or wind generation. The marginal emission data described in Section 3.4 is used to find the days with lowest emissions and maximum renewable energy generation. These days are then used to create a combined 8760-hour load profile that puts together normal-day (uncontrolled) operation and overheating operation for the two different load shifting schedules, depending on whether there is low emissions electricity available.

A histogram of the total greenhouse emissions in kg of CO_2 per kWh during the year 2017 (Figure 26 & Figure 27) shows the distribution of emissions per day during the year. As a simplified rule for operations, any day with a total intensity of emissions lower than the average found in the histogram used the controlled overheating simulation data for that day. Days with a higher number of emissions used the uncontrolled simulation data for that day.

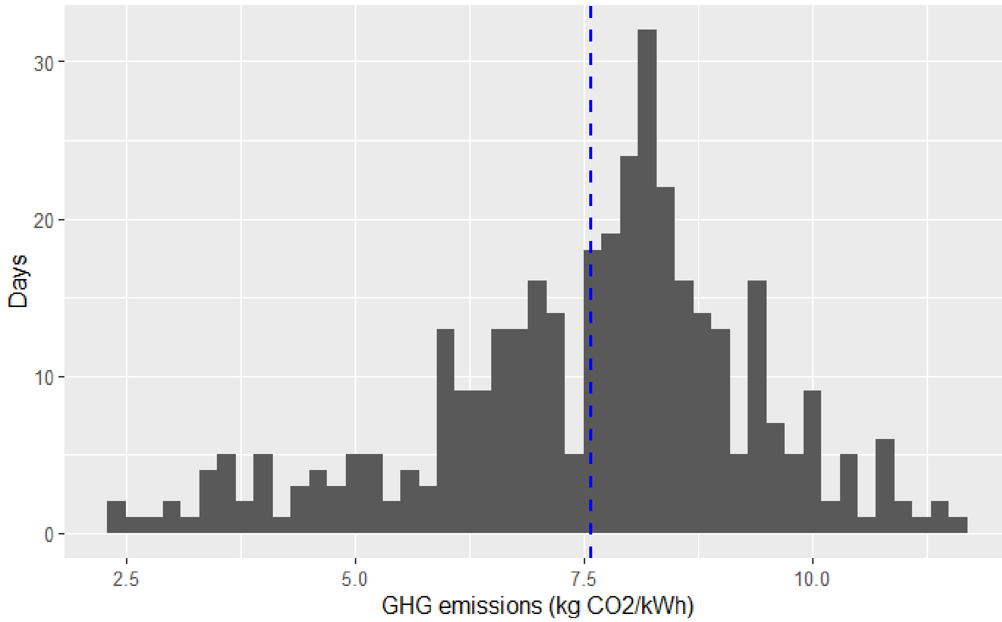

Figure 26. Distribution of emissions per day during 2017 for the NP15 (CPUC, 2017).

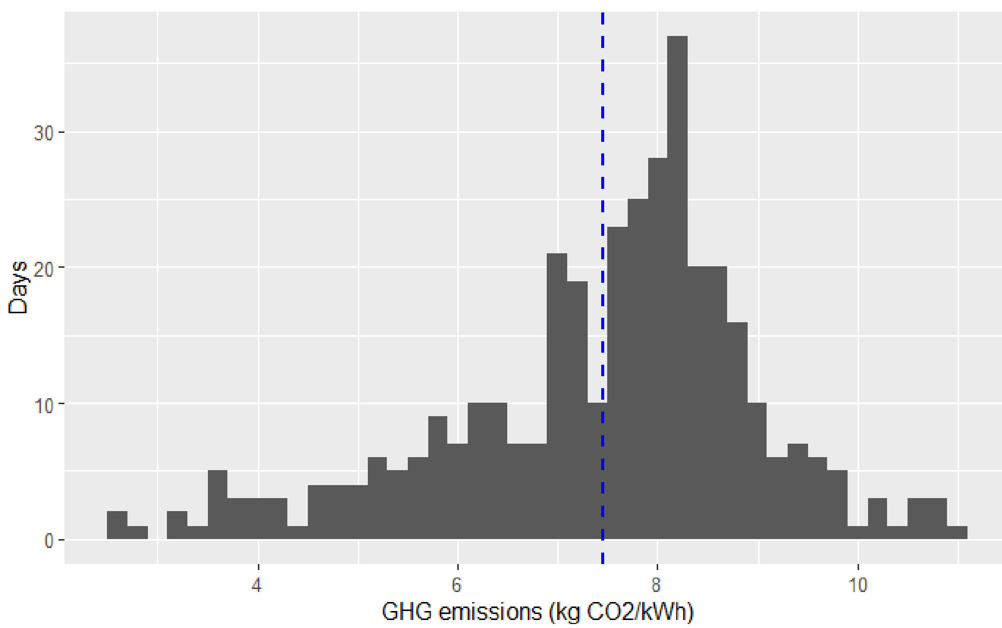

Figure 27. Distribution of emissions per day during 2017 for the SP15 (CPUC, 2017).

3.6- Utility Electricity Cost

The cost of electricity is calculated using the rate structure of four utility service territories, Pacific Gas & Electric (PG&E), Southern California Edison (SCE), Los Angeles Department of Water and Power (LADWP), and Sacramento Municipal Utilities District (SMUD). These utility territories cover the areas of the climate zones modeled in the building energy simulation (Figure 28). The rate structure used to calculate the electricity cost of the water heater operation is the time of use (TOU) rate structure. The cost of electricity per unit of energy (kWh) depends on the hour of the day it is used. Table 11 through Table 14 show the TOU rate structures of the different utilities used to calculate the cost of electricity in the corresponding climate zone.

A sensitivity analysis was performed to estimate the possible future cost of electricity using a proposed TOU rate structure that considers the surplus generation of solar power during the middle of the day. In this proposed rate structure, the cost of electricity during the solar peak is lower than the current off-peak PG&E rate. The proposed TOU for this time period is called super off-peak (SOP) and covers the hours between 10 am to 4 pm (Table 15). The proposed rate was used to calculate the electricity cost of the water heater operation in the simulated climate zone scenarios and compared with the current annual cost of the water heater operation.

Table 11. PG&E Residential TOU Rate Schedule E-TOU Option B (PG&E, 2020).

Summer	Peak Off-Peak	4 pm – 9 pm 9 pm – 8 am	$0.37119 $0.26813
Winter	Peak Off-Peak	4 pm – 9 pm 9 pm – 8 am	$0.23372 $0.21492

Table 12. SCE Residential Time-of-Use Rate (SCE, 2020).

Summer	Peak Off-Peak	4 pm – 9 pm 9 pm – 8 am	$0.37 $0.23
Winter	Mid-Peak Off-Peak Super-Off-Peak	4 pm - 9 pm 8 am - 4 pm 9 pm - 8 am	$0.32 $0.24 $0.22

Table 13. LADWP Residential Time-of-Use Rate (LADWP, 2020).

Summer	High-Peak Low-Peak Base	1 pm – 5 pm 10 am – 1 pm & 5 pm – 8 pm 8 pm – 10 am	$0.2612 $0.2028 $0.1754
Winter	High-Peak Low-Peak Base	1 pm – 5 pm 10 am – 1 pm & 5 pm – 8 pm 8 pm – 10 am	$0.2025 $0.2025 $0.1790

Table 14. SMUD Residential Time-of-Use Rate (SMUD, 2020)

Summer	Peak Mid-Peak Off-Peak	5 pm – 8 pm 12 pm – 5 pm & 8 pm – 12 am 12 am – 12 pm	$0.2941 $0.1671 $0.1209
Winter	Peak Off-Peak	5 pm - 8 pm 8 pm -5 pm	$0.1388 $0.1006

Table 15. PGE Residential Time-of-Use Rate pilot project, rate schedule E-TOUPP (PG&E, 2020).

Summer (Jun-Sept)	Peak Off-Peak	4 pm - 9 pm 9 pm – 8 am	$0.55485 $0.27743
Winter (Oct-May)	Peak Off-Peak	4 pm - 9 pm 9 pm – 8 am	$0.27935 $0.26040
Spring (Mar-May)	Peak Off-Peak Super-Off-Peak	4 pm - 9 pm 9 pm - 10 am 10 am – 4 pm	$0.34612 $0.25700 $0.17306

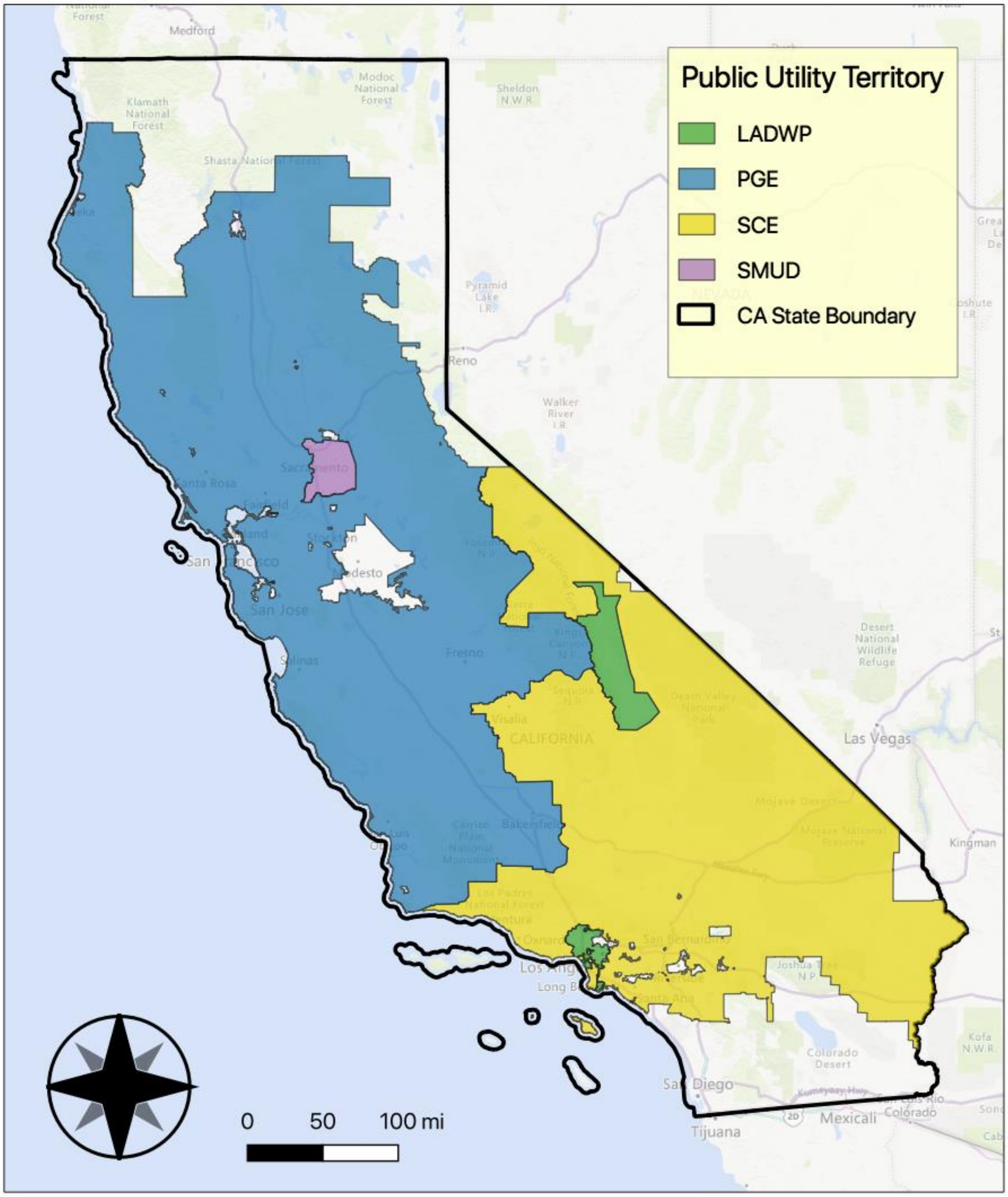

Figure 28. Public utility territory that cover the areas of the climate zones in the building energy modeling (CEC, 2019).

RESULTS

The hourly energy consumption of natural gas and electricity of water heaters in residential buildings was evaluated using industry standard and open source building energy simulation tools. Two building types were evaluated, a single family and a low-rise multifamily residence complex. The first section presents the results of the single-family and multifamily building energy simulation in Climate Zone 1. The second section presents the results of the building energy simulation by Climate Zone. Summary tables that compile the annual energy consumption, annual operation cost and annual GHG emissions from the simulated water heater types for the simulated climate zones are presented in Appendix A and Appendix B.

For each of the building types, a base case or uncontrolled scenario is modeled using a natural gas water heater, an electrical water heater and a heat pump water heater. These base case scenarios are compared to the controlled scenarios that simulate overheating the storage tank of the water heaters at different hours of the day. The simulation keeps the hot water draw profile, set point temperature, and inlet water temperature constant. The only variables are the water heating system and the TOU rates for the different scenarios and climate zones. The water hourly draw profiles reflect the most current algorithms and data incorporated in the 2019 CBECC Res software. Weather simulation files are based on the CEC Title 24 Typical Meteorological Year data to simulate a year of weather conditions (2016 Residential Alternative Calculation Method Reference Manual).

4.1- Building Energy Simulation - Climate Zone 1

The natural gas consumption of a NGWH heater follows a similar pattern to the daily water draw profile shown in Section 2.5. There is high use in the morning hours attributed to the use of showers, bathtubs, and hot water draws from faucets (Figure 29). The energy consumption profile of a multifamily building is similar to a single-family building but a larger magnitude (Figure 30). The energy profiles of an average day per month for a single-family residential building for the rest of the climate zones included in the simulation are shown in Appendix C.

The energy consumption depends on the amount and on the time that water is needed at an end point. The total annual energy consumption, annual operation cost, and annual GHG emissions of a NGWH for a single-family and a multifamily residential building in Climate Zone 1 is shown in Table 16.

Table 16. Annual operation parameters of a NGWH in Climate Zone 1 for a single-family and a multifamily building

	Single-family	**Multifamily**
Energy consumption (therms/year)	218	1,418
Operation cost ($/year)	314	2,042
GHG emissions ($lbCO_2$/year)	2940	19,070

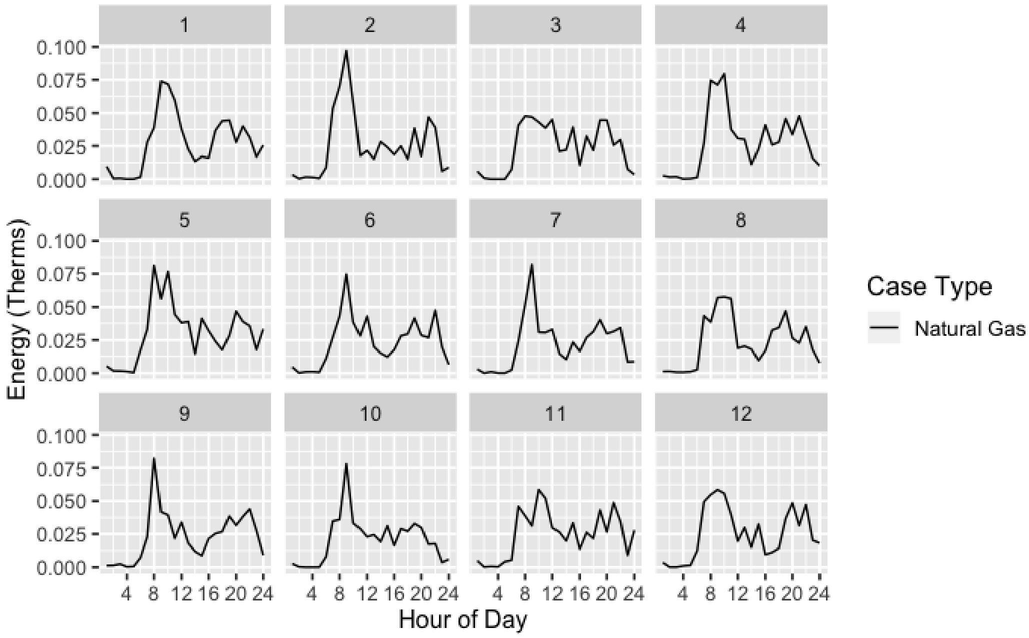

Figure 29. Natural gas consmption in an average day per month for NGWH in a single family building in Climate Zone 1.

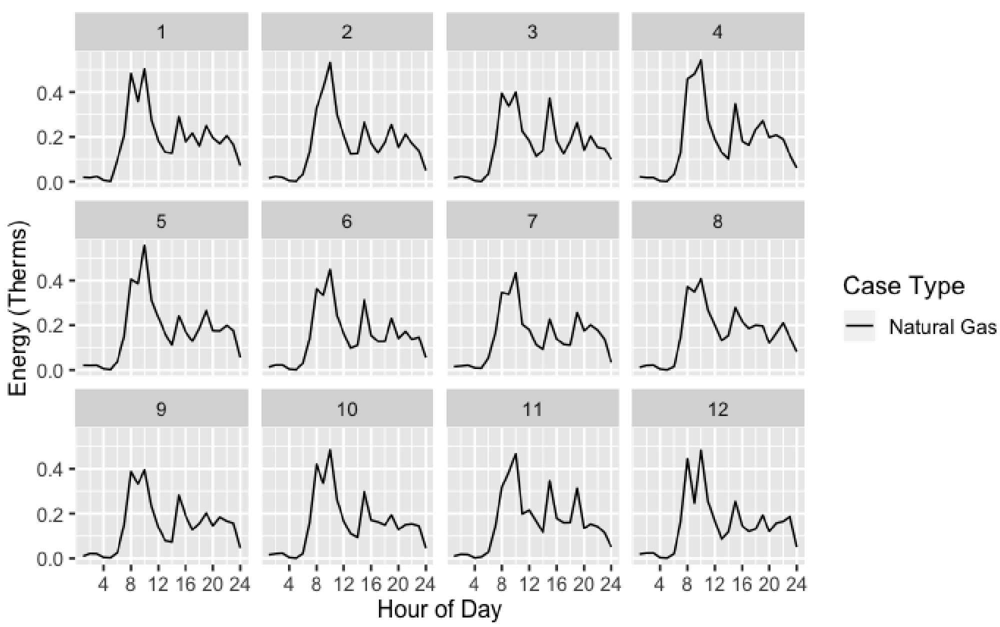

Figure 30. Natural gas consmption in an average day per month for NGWH in a multifamily building in Climate Zone 1.

The annual electricity consumption of the base case scenario of an ERWH in a single-family residential building (Figure 31) and a multifamily building (Figure 32) in Climate Zone 1 have a similar profile to the water draw profile shown in Section 2.5. The controlled scenarios of overheating the storage tank to 145ºF during the morning hours of 3 am to 6 am and between the hours of 10 am to 1 pm show a larger energy use during these hours of operation, as is expected (Figure 31 & Figure 32).

The electricity use spikes during these hours to match the hours of surplus renewable generation, low emissions, and lower TOU rates. The electricity consumption is lower during the later hours compared to the base case uncontrolled scenario. This is attributed to the capacity of the storage tank to store the thermal energy for later use during the day. The 3 am to 6 am overheating scenario shows a reduction in energy use during the peak water draw hours while the 10 am to 1 pm scenario shows a reduction in energy consumption in the afternoon hours (Figure 33 & Figure 34). The total annual energy consumption, operation cost, and GHG emissions of an ERWH for a single-family and a multifamily building in Climate Zone 1 is shown in

Table 17. The alternative scenario parameters are shown in Table 18 and Table 19.

Table 17. Base case scenario annual operation parameters of an ERWH in Climate Zone 1 for a single-family and a multifamily building.

	Single-family	**Multifamily**
Energy consumption (therms/year)	2,294	16,546
Operation cost ($/year)	850	4,666
GHG emissions ($lbCO_2$/year)	2,016	10,855

Table 18. Alternative scenario (overheating from 3 am to 6 am) annual operation parameters of an ERWH in Climate Zone 1 for a single-family and a multifamily building.

	Single-family	**Multifamily**
Energy consumption (therms/year)	3,069	17,254
Operation cost ($/year)	866	4,807
GHG emissions ($lbCO_2$/year)	2,075	11,547

Table 19. Alternative scenario (overheating from 10 am to 1 pm) annual operation parameters of an ERWH in Climate Zone 1 for a single-family and a multifamily building.

	Single-family	**Multifamily**
Energy consumption (therms/year)	3073	17,309
Operation cost ($/year)	849	4,706
GHG emissions ($lbCO_2$/year)	1910	10,123

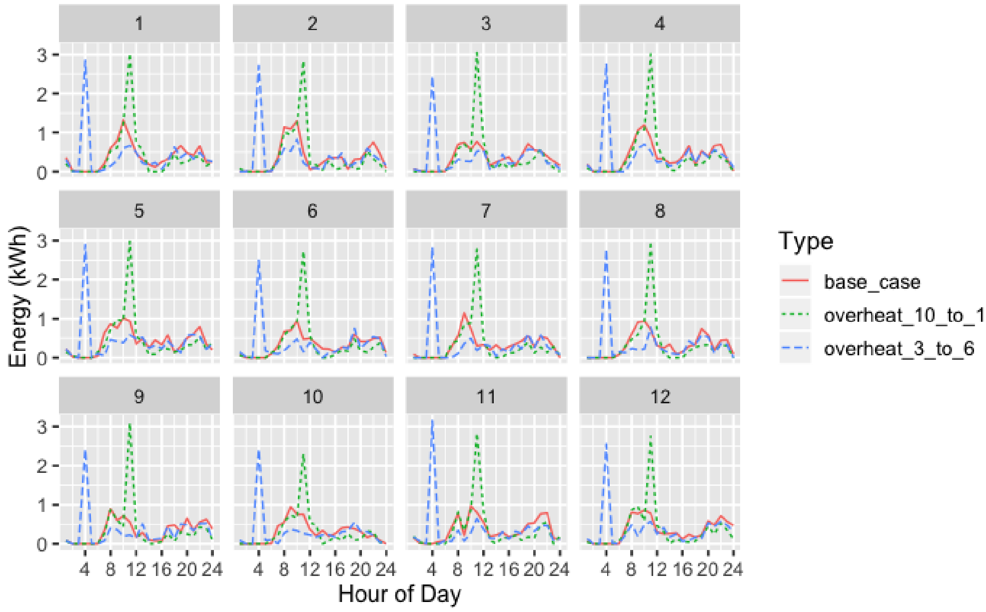

Figure 31. Electricity consumption in an average day per month for an ERWH in a single family building in Climate Zone 1. The “overheat 10 to 1” scenario involves pre-heating to 145F from 10 am to 1 pm while solar energy is available.

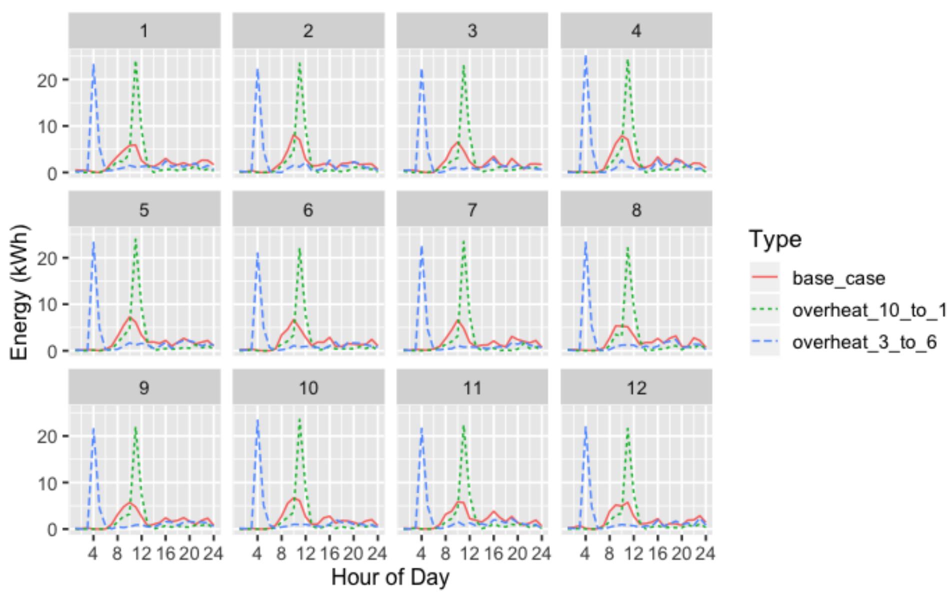

Figure 32. Electricity consumption in an average day per month for an ERWH in a multifamily building in Climate Zone 1. The “overheat 3 to 6” scenario involves pre-heating to 145F from 3 am to 6 am while TOU rates are usually lower.

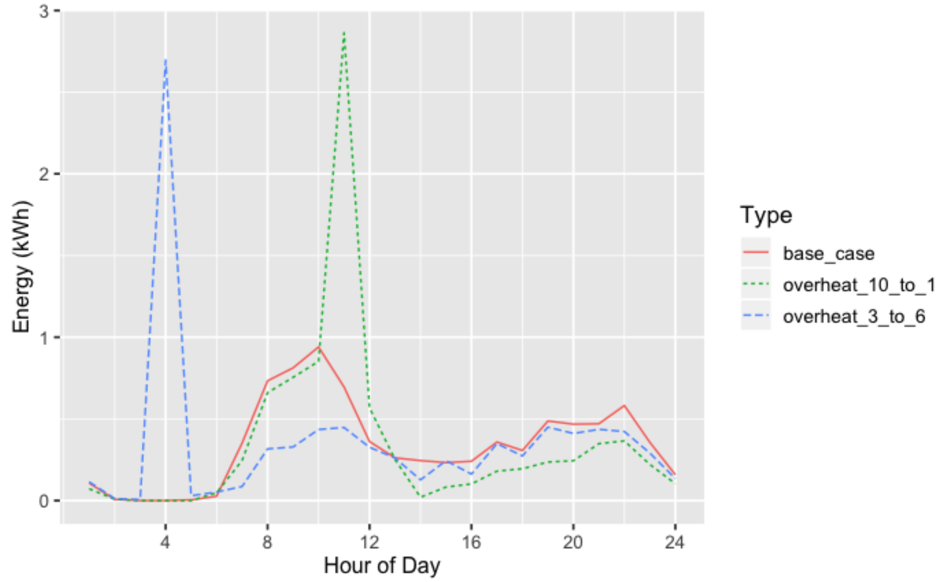

Figure 33. Electricity consumption in an average day of a year for an ERWH in a single family building in Climate Zone 1. The “overheat 10 to 1” scenario involves pre-heating to 145F from 10 am to 1 pm while solar energy is available.

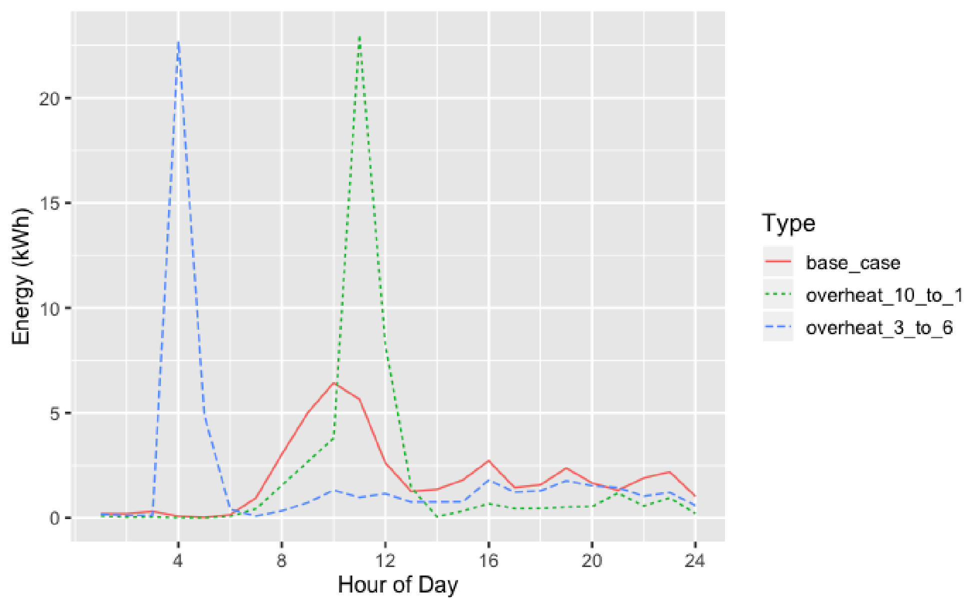

Figure 34. Electricity consumption in an average day per month for an ERWH in a multifamily building in Climate Zone 1. The “overheat 3 to 6” scenario involves pre-heating to 145F from 3 am to 6 am while TOU rates are usually lower.

The annual electricity consumption of the base case scenario of an HPWH in a single-family residential building (Figure 35) and a multifamily building (Figure 36) in Climate Zone 1 have a similar profile to the water draw profile shown in Section 2.5, following the trend of the daily hot water draw profile. The difference of the HPWH profile is that it has two heating components. The modeled HPWH is a hybrid model meaning that it has a compressor to work the refrigerant in the heat pump and an electrical resistance component "back up" that is active when the compressor cannot fully meet the demand for heat.

The controlled scenarios of overheating the storage tank show a larger energy use during the controlled hours of operation and lower use later. The 3 am to 6 am overheating scenario results in a reduction in energy use during the peak water draw hours (in the morning), while the 10 am to 1 pm scenario shows a reduction in energy consumption in the afternoon hours.

This is true for both the compressor and the electrical resistance back up. However, the backup resistance component is the one that shows a spike in energy consumption during the controlled hours of operation while the compressor energy consumption is higher during the uncontrolled hours of operation (Figure 37 & Figure 38).

The total annual energy consumption, operation cost, and GHG emissions of an ERWH for a single-family and a multifamily building in Climate Zone 1 is shown in Table 20. The alternative scenario parameters are shown in Table 21 and Table 22.

Table 20. Base case scenario annual operation parameters of a HPWH in Climate Zone 1 for a single-family and a multifamily building.

	Single-family	**Multifamily**
Energy consumption (therms/year)	1152	7,077
Operation cost ($/year)	326	1,998
GHG emissions ($lbCO_2$/year)	773	4,762

Table 21. Alternative scenario (overheating from 3 am to 6 am) annual operation parameters of a HPWH in Climate Zone 1 for a single-family and a multifamily building.

	Single-family	**Multifamily**
Energy consumption (therms/year)	1376	7,796
Operation cost ($/year)	386	2,157
GHG emissions ($lbCO_2$/year)	928	5,300

Table 22. Alternative scenario (overheating from 10 am to 1 pm) annual operation parameters of a HPWH in Climate Zone 1 for a single-family and a multifamily building.

	Single-family	**Multifamily**
Energy consumption (therms/year)	1383	7,725
Operation cost ($/year)	317	2,097
GHG emissions ($lbCO_2$/year)	850	4,627

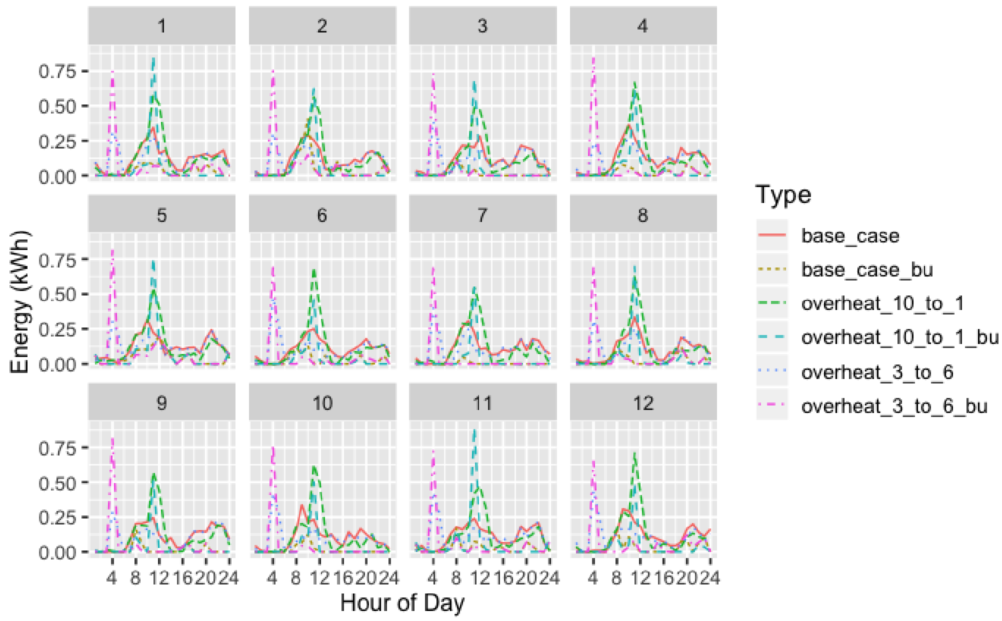

Figure 35. Electricity consumption in an average day per month for an HPWH in a single family building in Climate Zone 1.

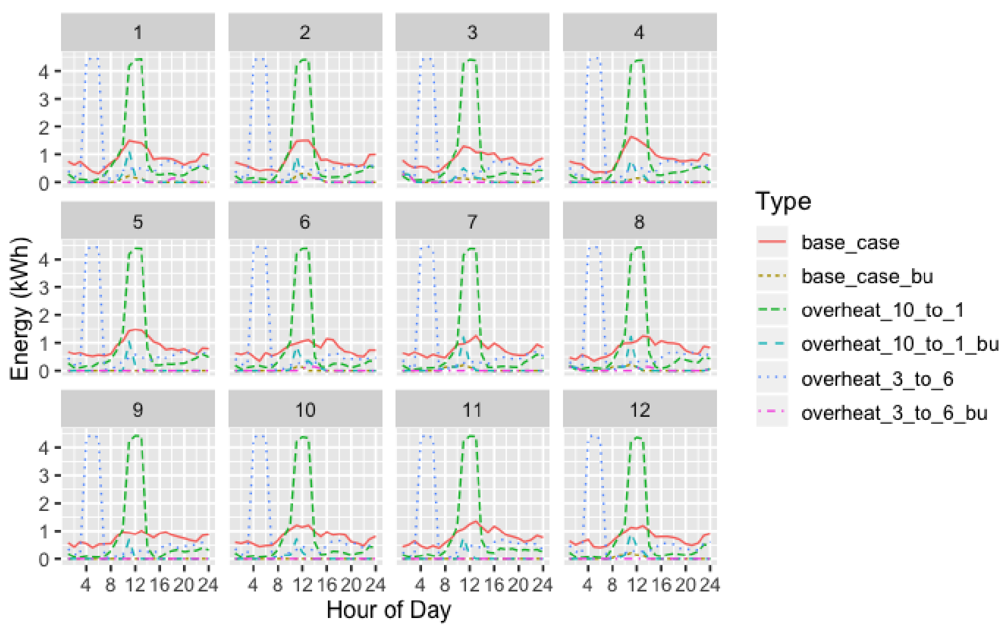

Figure 36. Electricity consumption in an average day per month for an HPWH in a multifamily building in Climate Zone 1.

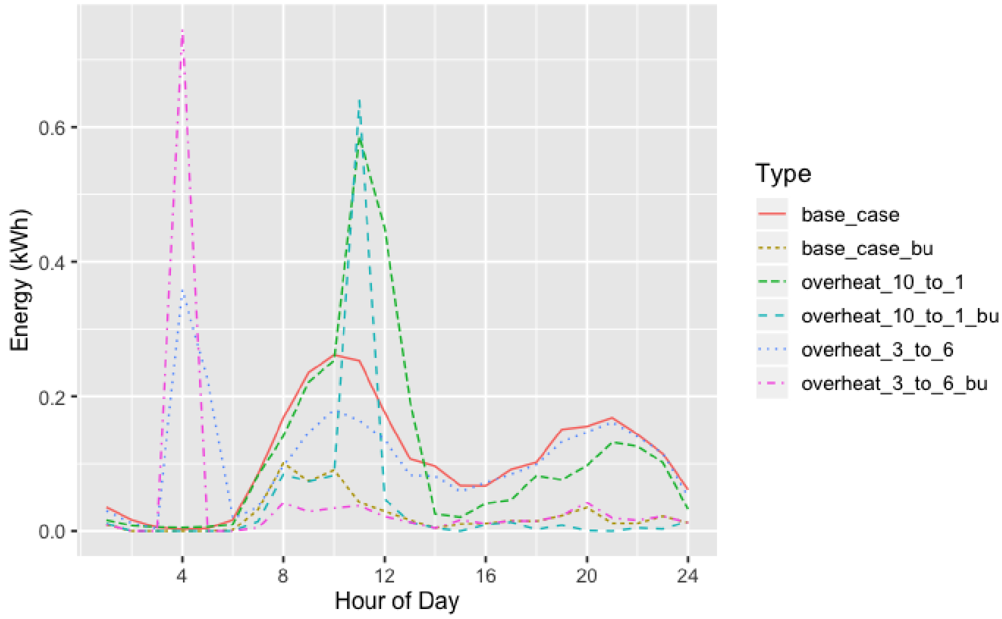

Figure 37. Electricity consumption in an average day of a year for an HPWH in a single family building in Climate Zone 1.

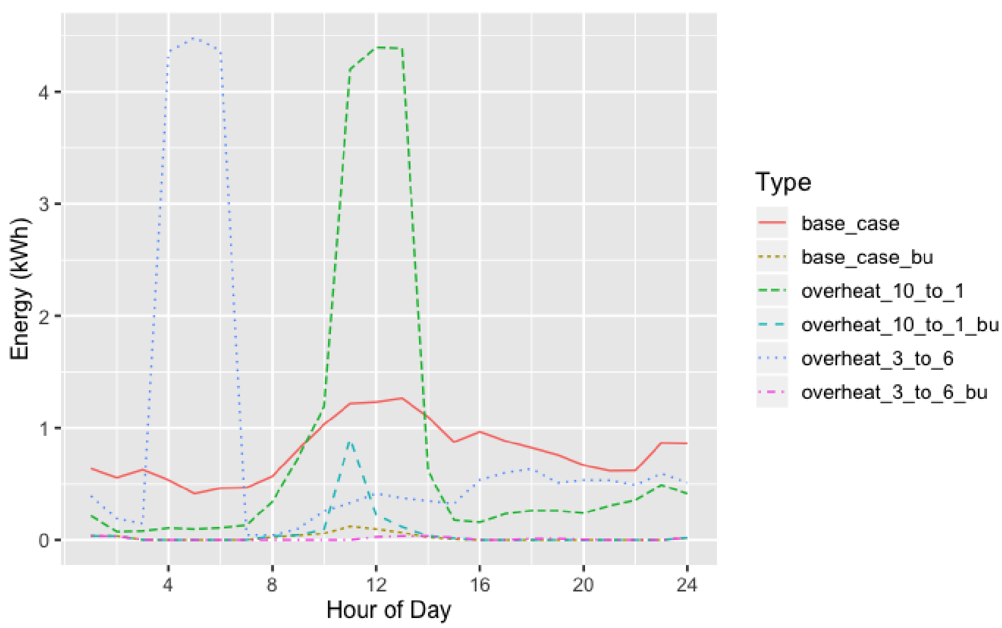

Figure 38. Electricity consumption in an average day per month for an HPWH in a multifamily building in Climate Zone 1.

As mentioned in Section 3.5 (Modeling Approach), a “mixed” scenario of normal operation (uncontrolled) on days with higher than average emissions and overheating (controlled) operation on days with lower emissions was created to compare the annual energy use, cost, and GHG emissions with the other scenarios. The model result shows an annual energy reduction of 18% in the mixed scenarios for the HPWH compared to the “overheat every day” scenario. The ERWH mixed scenario from 10 am to 1 pm has a larger consumption during the year while the 3 am to 6 am scenario shows a 4% energy reduction (**Error! Reference source not found.**) compared to the base case scenario. The annual cost of operation of an ERWH in Climate Zone 1 is more than twice the HPWH and the NGWH (Figure 39 & Figure 40). The high cost of the ERWH is attributed to the high electricity consumption of the resistance elements used to heat the water in the storage tank and relatively high cost of electricity. The annual cost of operation for a HPWH is lowest during the 10 am to 1 pm mixed case scenario, showing the opportunity to have a similar and competing cost with a NGWH.

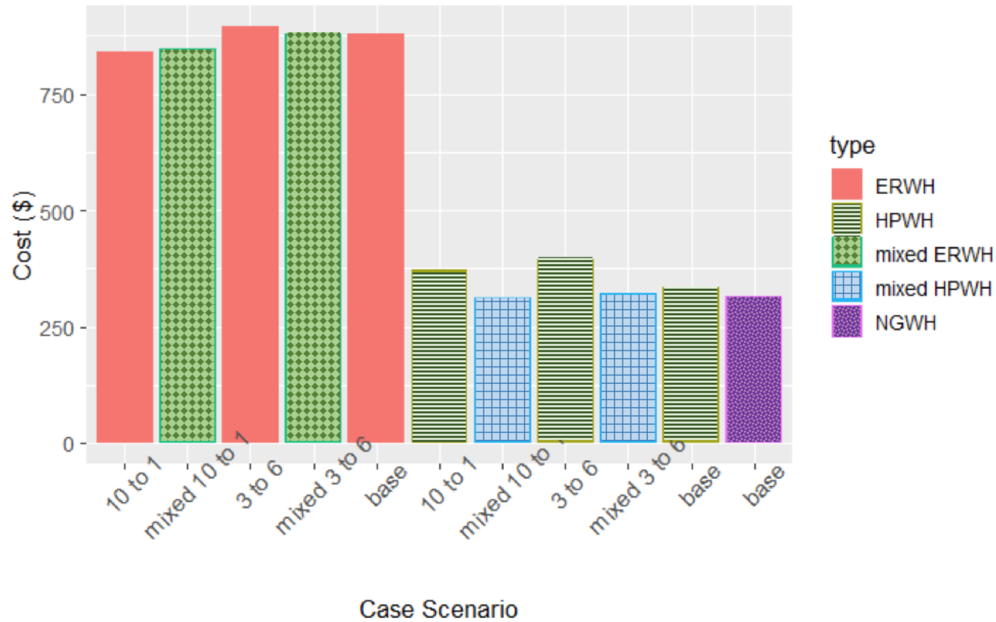

Figure 39. Annual cost of operation for different water heating systems and modeled scenarios in a single family building in Climate Zone 1.

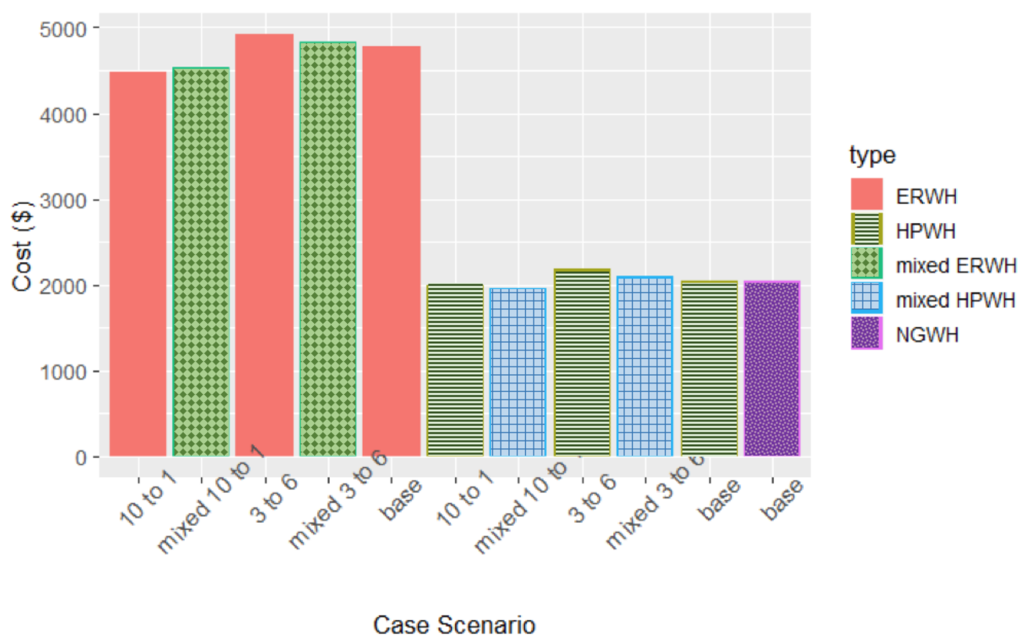

Figure 40. Annual cost of operation for different water heating systems and modeled scenarios in a multifamily building in Climate Zone 1.

The annual GHG emissions from the NGWH are about 30% and 60% higher than the ERWH and the HPWH, respectively. The HPWH GHG annual emission are the lowest of the three modeled water heating systems. The mixed case scenario of overheating from 10 am to 1 pm on days wiith low emissions intensity shows the lowest GHG emissions. This is based on using more electricity on days where the marginal emission data is the lowest hours of emissions during the solar peak generation in the NP15 path.

Using an efficient water heater system during these hours shows benefit in lower cost and GHG emission reduction (Figure 41 & Figure 42). The high number of GHG emissions from the NGWH make it a lower value option when compared to a more efficient HPWH. Even if the equivalent cost of natural gas for a similar use is lower than electricity, the quantity of GHG emissions and the social costs associated with natural gas extraction and carbon emissions make the HPWH a better alternative for residential use.

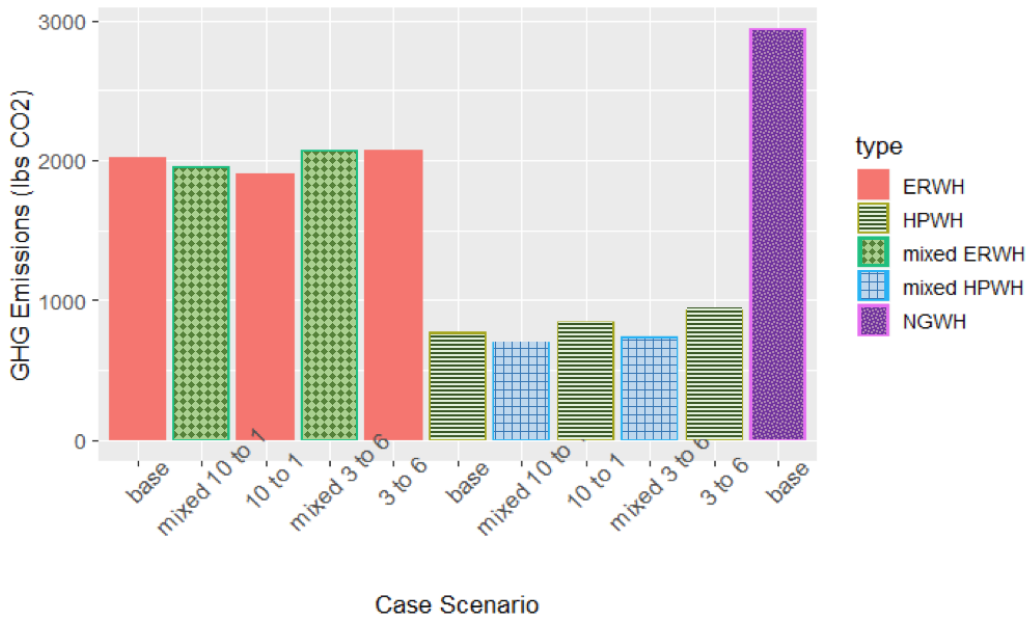

Figure 41. Annual GHG emissions from different water heating systems and modeled scenarios in a single family building in Climate Zone 1.

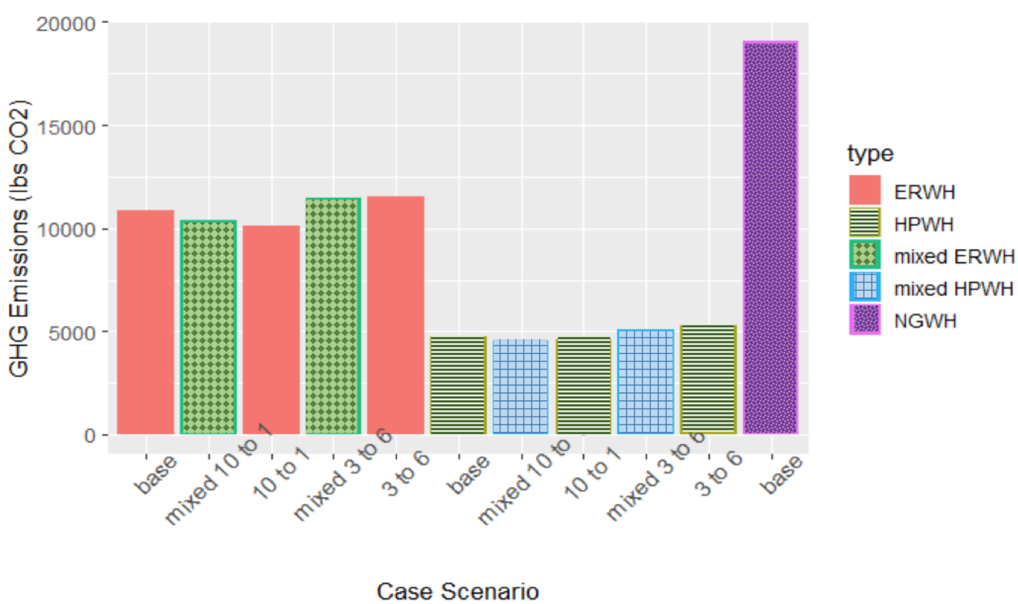

Figure 42. Annual GHG emissions from different water heating systems and modeled scenarios in a multifamily building in Climate Zone 1.

4.2- Building Energy Simulation Results by Climate Zone

The following section presents the results of the building energy simulation for single-family and multifamily residence buildings across the different climate zones modeled. The results shown are from the mixed case scenarios since these represent a more realistic mode of operation rather than overheating every day of the year without any control parameter.

The electricity consumption of an ERWH is about 60% higher than a HPWH for all climate zones (Figure 43, Figure 44 & **Error! Reference source not found.**). The modeled ERWH has a 0.92 UEF and the HPWH has a 3.5 UEF. A higher UEF means a water heater is more efficient and will cost less to operate compared to other water heaters with a similar storage tank capacity. The HPWH can provide the same amount of DHW as the ERWH with a lower energy input.

The 3 am to 6 am mixed case shows the lowest energy consumption in all climate zones, overheating the storage tank in the early morning hours before the high peak hours of hot water draws has the highest benefit in thermal energy storage.

Both ERWH and the HPWH require less energy to operate in Climate Zones 6, 9, and 10. These climate zones are in the southern part of the state and have higher ambient temperatures especially during the summer months (Figure 45). A higher ambient temperature means that the inlet water into the storage tank has a higher temperature and requires less energy input to reach the set point temperature of the tank.

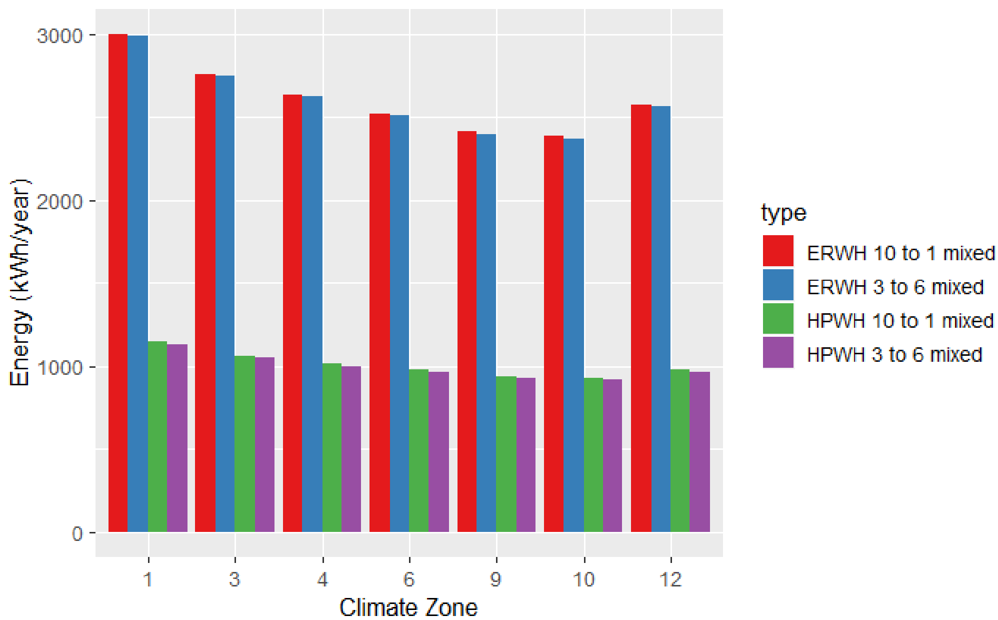

Figure 43. Annual energy consumption of different water heater types in single family building in all climate zones included in the building energy model.

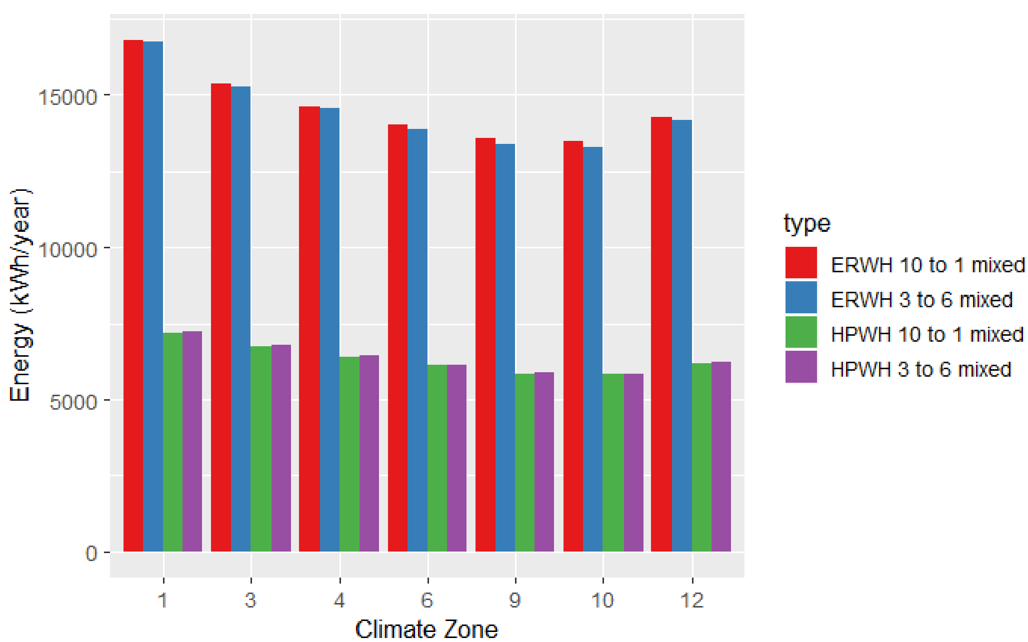

Figure 44. Energy consumption of different water heater types in single family building in all climate zones included in the building energy model.

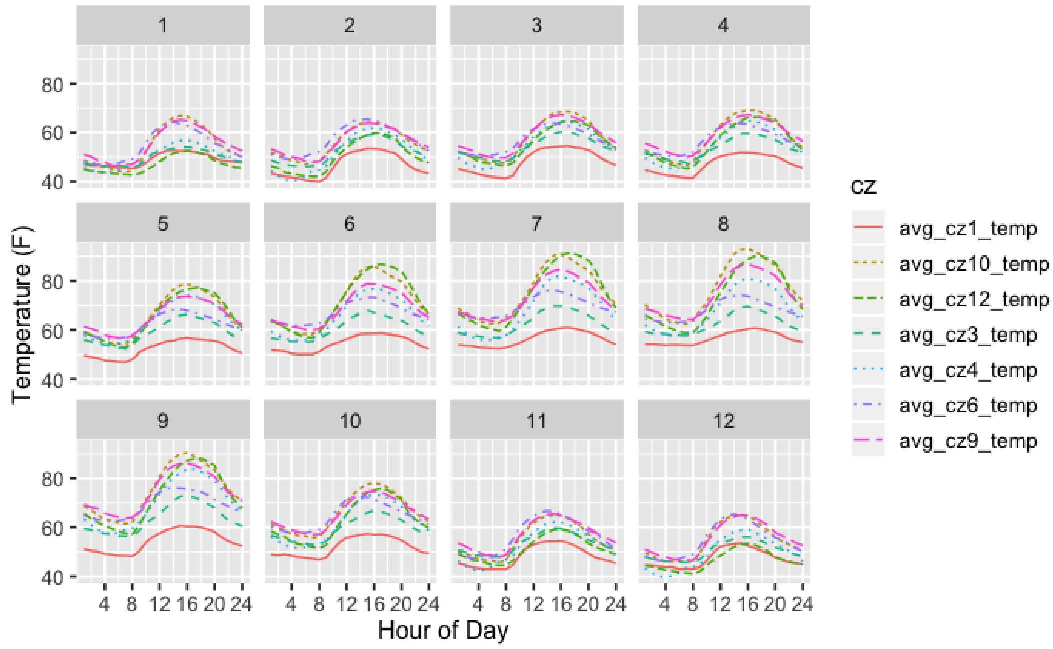

Figure 45. Ambient temperature of an average day per month in all climate zones included in the building energy model.

The annual cost of operation is lower in climate Zones 9 and 12 for all water heater types when compared to the rest of the climate zones (Figure 46, Figure 48 & **Error! Reference source not found.**). This is not only because of lower energy consumption but also due to the lower TOU electricity prices from Los Angeles Department of Water and Power (LADWP) and the Sacramento Municipal Utilities District (SMUD).

The ERWH operation cost is the highest for all climate zones. Climate Zones 1, 2, and 3 have a milder ambient temperature throughout the year. This makes the cost of operation between the HPWH and the NGWH to be similar. The rest of the climate zones have higher temperatures during the year, which makes the HPWH a more cost-effective option when compared to the NGWH, especially in the Climate Zones 9 and 12 with lower TOU rates (Figure 46 & Figure 48).

The annual cost of operation when using the PG&E proposed TOU rate stays close to the annual cost when using the current rates for climate zones in the PG&E territory (Figure 47 & Figure 49). SMUD and LADWP already have a low TOU rate cost, so utilizing the proposed PG&E rates makes the annual operation higher (**Error! Reference source not found.**).

The lower cost during the solar generation peak is balanced with a higher cost in the afternoon (Figure 50). This proposed TOU rate structure incentivizes the use of electricity during the super-off-peak (SOP) hours between 10 am to 3 pm when the surplus solar generation occurs. A HPWH can operate the compressor and the electrical resistance units during these hours to overheat the water in the storage tank and use the thermal energy stored during the afternoon hours.

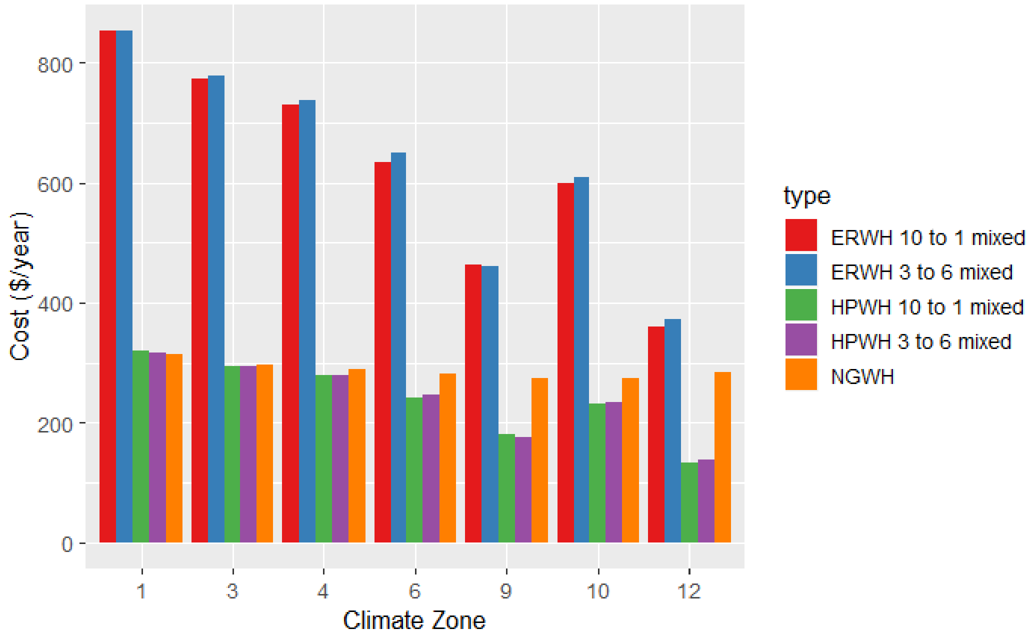

Figure 46. Annual cost of operation using current TOU rates in a single-family building.

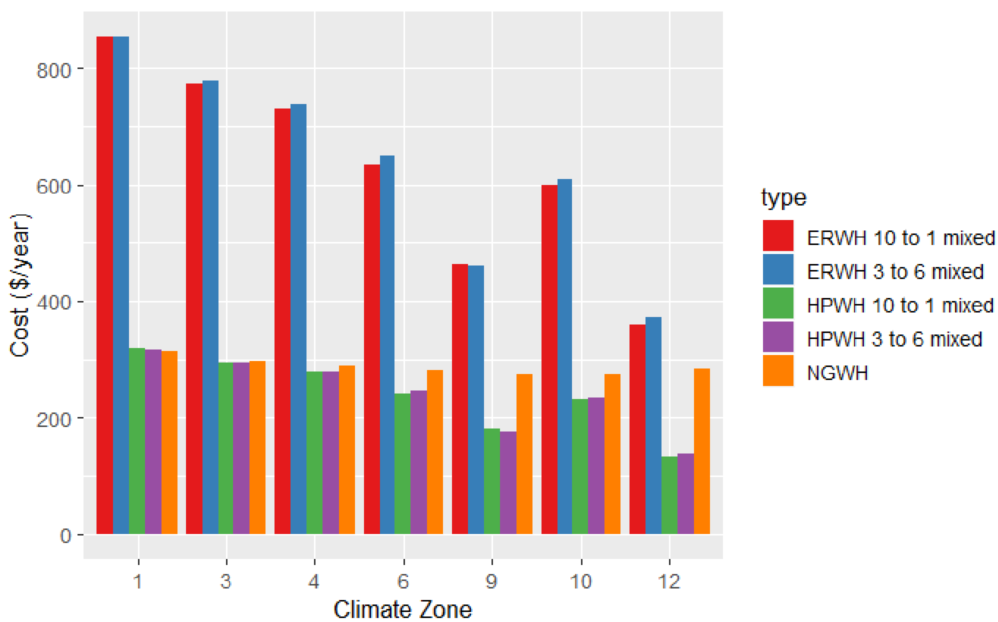

Figure 47. Annual cost of operation using PG&E proposed TOU rates in a single-family building.

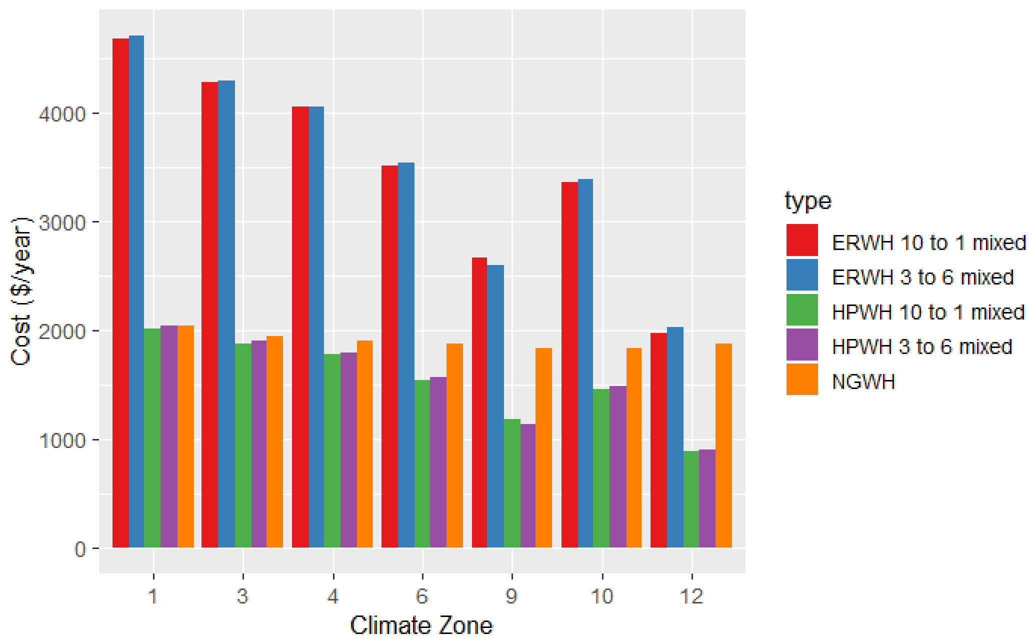

Figure 48. Annual cost of operation using current TOU rates in a multifamily building.

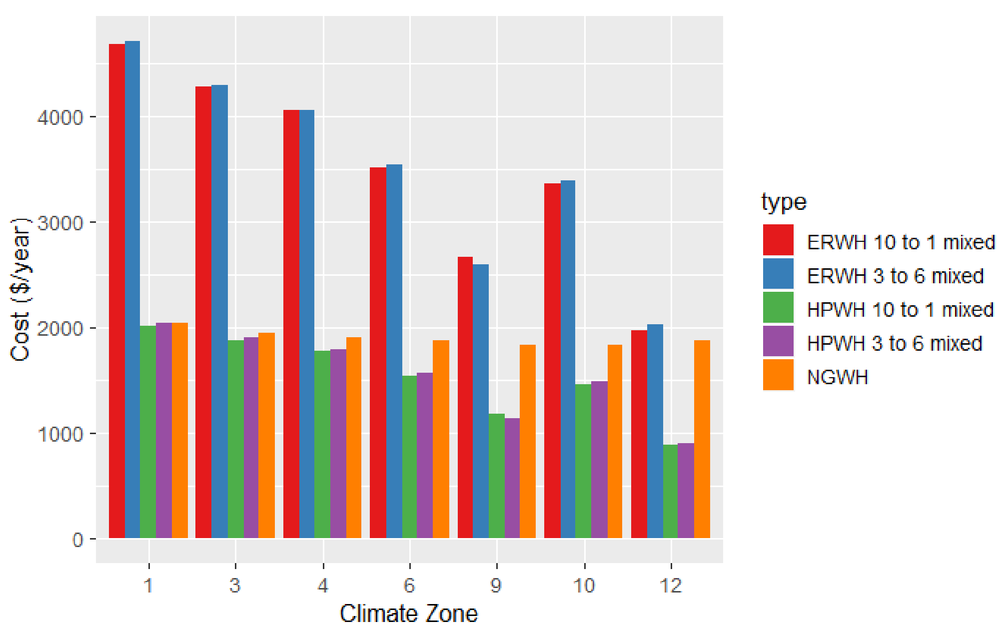

Figure 49. Annual cost of operation using proposed PG&E TOU rates in a multifamily building.

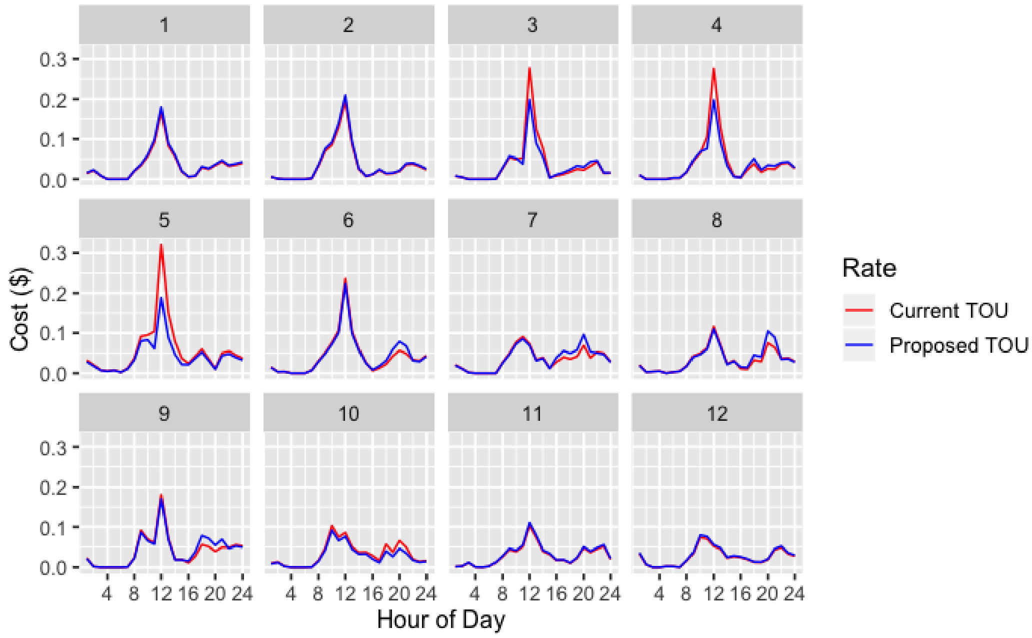

Figure 50. Cost of operation in an average day per month of HPWH in Climate Zone 1 using the current TOU rate and the proposed TOU rate from PG&E.

The NGWH is the one with the highest quantity of GHG emission per year, followed by the ERWH and then the HPWH. The HPWH emissions per year are about 70% less than the NGWH and about half of the emissions from the ERWH for all climate zones. Climate Zones 6, 9, and 10 have a lower quantity of emissions per year due to the higher ambient temperature during the year. There is less energy required for these climate zones during the summer months and therefore less GHG emissions associated with water heating (Figure 51, Figure 52 & **Error! Reference source not found.**). For the ERWH and the HPWH the operation mode of overheating the tank between the hours of 10 am and 1 pm provides an emissions reduction benefit compared to the 3 am to 6 am case. The GHG emissions are lower during the middle of the day when the solar generation is higher, and the fossil fuel power plants have lower output.

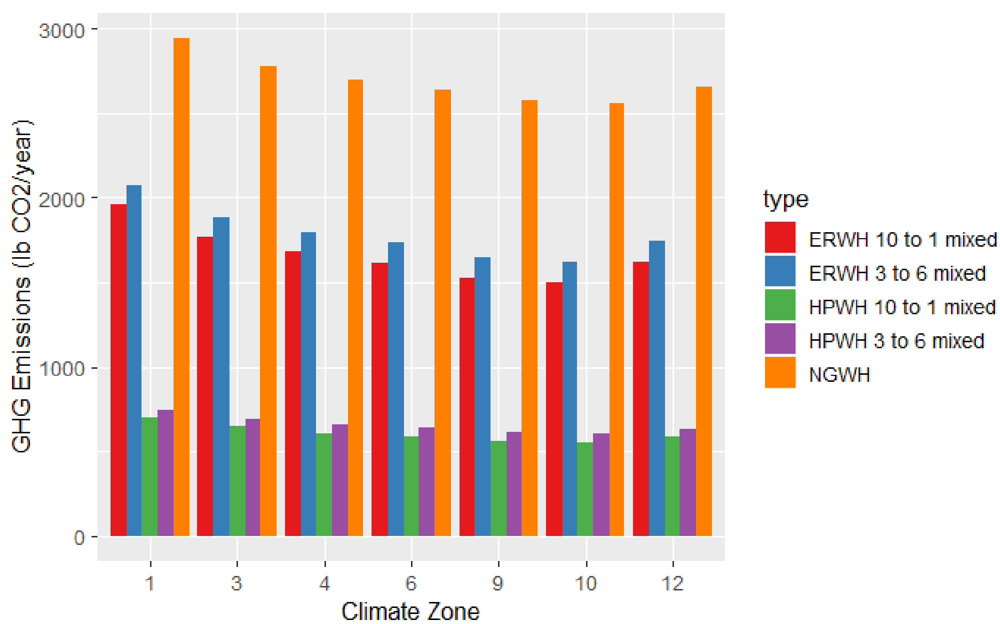

Figure 51. Annual GHG emissions from different water heater types in a single-family building in all climate zones included in the building energy model.

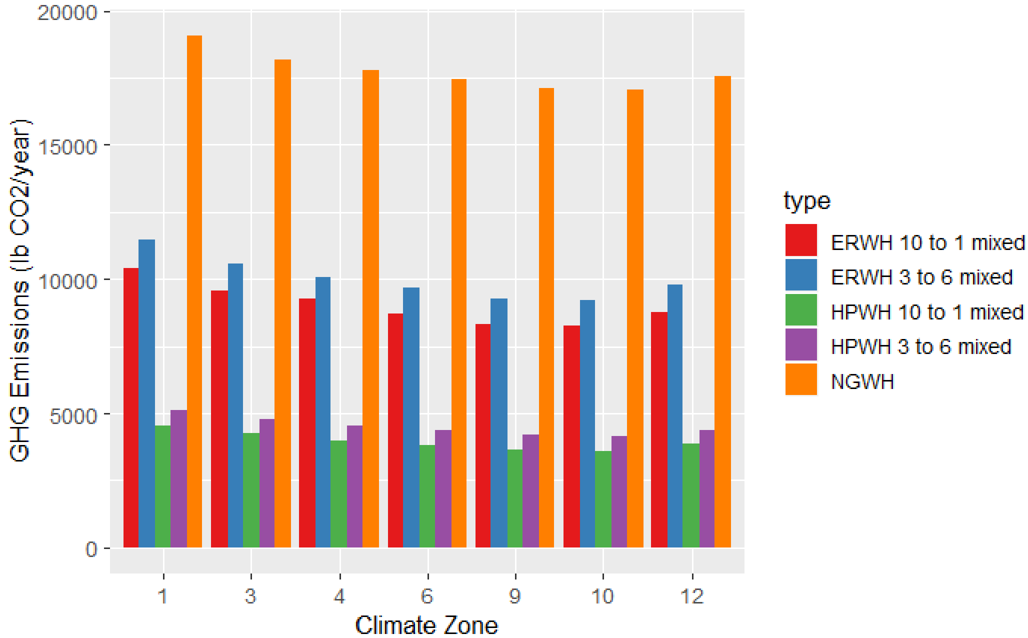

Figure 52. Annual GHG emissions from different water heater types in a multifamily building in all climate zones included in the building energy model.

DISCUSSION

The results showing the benefits of controlling the timing of water heater operation show the potential of using HPWH and ERWH technology to participate in demand response management programs. The demand response capability of HPWH and ERWH show that they could be useful tools to accommodate surplus energy from solar generation during the solar peak hours. Whether the demand response is implemented using traditional HPWH or ERWH units, the capability of the technology to act on control signals is a necessary condition for a successful program.

One of the differences between HPWHs and ERWHs is that HPWHs have a higher efficiency and lower overall energy consumption, and the effective electrical energy storage capacity is lower than an ERWH for a similar size tank. There is simply fewer energy (kWh) involved in heating a gallon of water in a HPWH than in an ERWH.

Another difference is that the HPWH operation switches between compressor and electrical resistance mode. To maximize water heating efficiency, it is important to use the heat pump only modes when preheating water during the off-peak hours in order to avoid energizing the resistance elements unnecessarily. This added control complexity can be an advantage by enabling more advanced logic systems that can optimize the combination of a water heating efficiency. With most of the water draws occurring during the day, operating water heaters at higher temperatures in the controlled hours reduces the likelihood of the electric resistance element being energized in the late afternoon peak hours.

Average use patterns showed that the energy use was lower during peak periods as planned. Overall, the controlled scenario simulations show a lower electricity consumption than the uncontrolled group. These are relatively small energy savings per water heater, but an aggregated use of controlled water heaters can be an opportunity for demand response programs.

The ability to recognize patterns in hot water use and optimize the mode and temperature settings to individual residences suggest that HPWHs participating in a demand response management program can both reduce the average electrical energy use during peak load hours and store energy without sacrificing overall energy efficiency.

The results show that HPWHs are a cost-effective alternative compared to ERWHs and NGWHs. The benefits can be seen in overall lower energy consumption, lower cost of operation, and lower greenhouse gas emissions. The HPWH results show that it can be a competing technology with NGWH, as the annual operation cost is approximately the same while providing an opportunity for GHG emissions reductions.

The largest market barrier for heat pump water heaters for residential buildings is the initial high cost. However, the energy savings, in most cases, will offset the high capital cost in a few years. Still, this does not provide enough of an incentive for customers to select HPWHs for retrofits or new installations. Outreach from manufactures and rebate programs from utility companies could be implemented to expand the implementation of HPWH technology in residential buildings. Mandating existing homes to be retrofit or replacing appliances with non-conventional heating equipment could be expensive and difficult. The main market barriers to HPWH adoption are (Hopkins, Takahashi, Glick, & Whited, 2018):

- HPWHs require access to large volume of air, which means they must be installed in large enough rooms (basement, garage, laundry) or be ducted to the outside. This complicates replacement / installation and can increase cost.
- Building energy codes have favored tankless gas water heaters, requiring additional analysis to justify a HPWH.
- HPWH upgrade could require an electric panel upgrade, although there are several options which require only an additional 15-Amp circuit breaker. Typical hybrid HPWHs require 30 Amps, but Sanden CO_2 HPWHs use 15 Amps and Rheem has recently introduced models that require only 15-Amp service.

There are however some promising market opportunities for the adoption of HPWHs:

- New construction sites can optimize for the location of the water heater, and the necessary level of electric service can be installed.
- Utility territories with relatively low electric rates compared to natural gas or where gas service is not available can benefit from HPWHs.
- Multifamily buildings, where larger tanks (which help to avoid the need for electric resistance to supplement the heat pump) and “ganged” water heaters (multiple units used in parallel) can effectively meet multiple units’ needs.
- A gain in market shares of HPWH could result in economies of scale in manufacturing and learning by doing that brings down the installed costs.

CONCLUSION AND RECOMMENDATIONS

Water heating technology was simulated using the Building Energy Modeling software California Building Energy for Code Compliance (CBECC-Res) and the California Simulation Engine (CSE). Different climate zones were explored to compare the electricity needed for a water heater operation given the same input parameters of water draw profiles and building envelope. The building climate zones are summarized by weather data, and the energy use depends partly on climate conditions which differ throughout the state.

Water heater production can be optimized to save energy while still meeting service demand, and the thermal storage capability of the water heater tank can be used as a battery to store energy for later use during the day. Smart control technology can enable water heaters to shift the timing of electricity demands to avoid the high electric rates under a time of use rate schedule. The results show that HPWH are the most efficient technology in terms of energy use, operation cost, and greenhouse gas emissions. Demand response programs can be implemented and designed according to the different electricity rate schedules for each utility in the state. In general, the patterns for preheating water heater storage tanks are the same for all climate zones. Preheating the storage tank before the peak hours of hot water draws can reduce energy consumption during cost-peak hours. The integration of solar generation into the California grid could be eased by the aggregated use of electrical water heaters, including heat pumps.

Most households in the U.S. use natural gas to heat water. A typical gas storage water heater has an Energy Factor (efficiency rating) of about 0.6, while a typical electric storage water heater is rated about 0.9. Based on these Energy Factors it would seem an electric water heater uses less energy. Actually, the opposite is true, as it takes about three times as much source energy (this includes the energy needed to generate and distribute a fuel) to deliver electricity to a home compared to natural gas. This is because only about 1/3 of the fuel energy burned at the utility's power plant reaches a home in the form of electricity. The rest is lost due to inefficiency at the power plant and over power lines. Therefore, an electric water heater that appears to be 50% “better” than a gas one (0.9 Energy Factor versus 0.6 Energy Factor) actually uses much more source energy than the gas water heater (CEC, 2017). It is for this reason that when performance modeling a new electric water heater for California building code compliance there is a significant penalty. Therefore, it is important to update the current codes to account for renewable and cleaner methods of power generation.

The HPWH configuration for a multifamily building can be different from single family residences. Multifamily buildings can have a central hot water system based on an appropriately sized HPWH or a group of smaller residential scale products hooked together to serve a common load. The availability of large HPWH models is limited compared to residential models, but several companies offer large scale HPWH products in the U.S. market.

While we will need electric storage to support the hours when neither wind nor solar energy is available, behavior-driven energy shifting to periods of excess renewables is a zero-cost measure, and appliances with built-in capability, such as water heaters, are a near-zero-cost measure in the end-state. Decarbonizing the residential hot water sector in California can help reduce the amount of GHG emissions and help the integration of renewables into the grid by providing thermal storage capability. The cost of the fuel switch will depend on the future cost of heat pump technology, electricity rates, and hot water consumption.

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APPENDIX A

Appendix A: Building energy modeling results for a single-family building. Includes summary tables of the energy consumption, cost of operation, and GHG emissions for the three different water heater types (NGWH, ERWH, HPWH) in the building energy modeling for all included climate zones.

Table A- 1. Annual energy consumption in a single-family building - base case scenario

Climate Zone	Representative City	NG (Therms)	ERWH (kWh)	HPWH (kWh)
1	Arcata	218	2994	1152
3	San Francisco	206	2715	1032
4	San Jose	200	2590	972
6	Coastal LA	195	2480	929
9	Downtown LA	191	2376	883
10	Riverside	190	2358	877
12	Sacramento	197	2522	945

Table A- 2. Annual energy consumption in a single-family building - controlled scenarios

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	3069	3073	2993	2998	1376	1383	1132	1152
3	2792	2798	2753	2759	1257	1269	1049	1064
4	2670	2676	2631	2637	1195	1205	998	1013
6	2558	2566	2511	2521	1149	1160	965	979
9	2376	2464	2399	2417	1101	1115	925	938
10	2439	2447	2374	2391	1096	1102	917	928
12	2601	2608	2565	2578	1162	1173	966	984

Table A- 3. Annual cost of operation in a single-family building using the current TOU rate structure - base case scenarios

Climate Zone	Representative City	NG ($/year)	ERWH ($/year)	HPWH ($/year)
1	Arcata	314	850	326
3	San Francisco	297	772	291
4	San Jose	289	729	273
6	Coastal LA	282	648	241
9	Downtown LA	275	456	169
10	Riverside	274	610	227
12	Sacramento	284	378	139

Table A- 4. Annual cost of operation in a single family-building using the current TOU rate structure - controlled scenarios

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	866	849	853	853	386	381	317	320
3	785	767	778	772	350	347	293	295
4	746	729	737	731	332	327	278	279
6	658	622	648	634	290	280	246	242
9	466	461	460	462	209	209	177	181
10	625	591	609	598	275	265	234	230
12	375	338	371	359	163	150	137	134

Table A- 5. Annual cost of operation in a single-family building using the proposed PG&E TOU rate structure - base case scenarios

Climate Zone	Representative City	NG ($/year)	ERWH ($/year)	HPWH ($/year)
1	Arcata	314	881	335
3	San Francisco	297	803	300
4	San Jose	289	754	281
6	Coastal LA	282	725	268
9	Downtown LA	275	692	255
10	Riverside	274	679	252
12	Sacramento	284	731	271

Table A- 6. Annual cost of operation in a single-family building using the proposed PG&E TOU rate structure - controlled scenarios

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	895	839	878	848	396	372	321	311
3	810	752	803	768	358	337	299	287
4	770	714	756	723	339	317	283	271
6	741	684	725	694	327	305	274	262
9	706	651	692	662	311	291	263	251
10	698	645	678	651	309	287	260	248
12	747	691	735	705	328	307	275	262

Table A- 7. Greenhouse Gas emissions from water heater operation in a single-family building - base case scenario

Climate Zone	Representative City	NG (lb CO_2/year)	ERWH (lb CO_2/year)	HPWH (lb CO_2/year)
1	Arcata	2940	2016	773
3	San Francisco	2773	1832	693
4	San Jose	2698	1735	650
6	Coastal LA	2634	1671	619
9	Downtown LA	2572	1590	584
10	Riverside	2561	1571	580
12	Sacramento	2656	1678	627

Table A- 8. Greenhouse Gas emissions from water heater operation in a single-family building - controlled scenarios

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	2075	1910	2077	1960	928	850	745	701
3	1871	1724	1881	1768	839	773	694	647
4	1786	1636	1793	1678	795	724	657	610
6	1734	1554	1733	1611	766	696	641	588
9	1656	1468	1648	1525	727	662	612	560
10	1638	1462	1622	1502	725	650	606	552
12	1734	1575	1740	1625	769	701	634	589

APPENDIX B

Appendix B: Building energy modeling results for a multifamily building. Includes summary tables of the energy consumption, cost of operation, and GHG emissions for the three different water heater types (NGWH, ERWH, HPWH) in the building energy modeling for all included climate zones.

Table B- 1. Annual energy consumption in a multifamily building - base case scenario

Climate Zone	Representative City	NG (Therms)	ERWH (kWh)	HPWH (kWh)
1	Arcata	1418	16546	7077
3	San Francisco	1351	15044	6506
4	San Jose	1321	14346	6160
6	Coastal LA	1296	13726	5895
9	Downtown LA	1272	13160	5628
10	Riverside	1267	13064	5576
12	Sacramento	1304	13963	5957

Table B- 2. Annual energy consumption in a multifamily building - controlled scenario

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	17254	17309	16751	16803	7796	7725	7258	7206
3	15758	15825	15265	15347	7222	7162	6772	6722
4	15071	15117	14570	14635	6883	6834	6432	6378
6	14453	14522	13869	14035	6591	6556	6145	6135
9	13901	13968	13387	13569	6326	6314	5885	5867
10	13806	13876	13298	13486	6285	6279	5832	5824
12	14695	14757	14162	14255	6682	6642	6231	6187

Table B- 3. Annual cost of operation in a single-family building using the current TOU rate structure - base case scenarios

Climate Zone	Representative City	NG ($/year)	ERWH ($/year)	HPWH ($/year)
1	Arcata	2042	4666	1998
3	San Francisco	1946	4251	1844
4	San Jose	1902	4030	1735
6	Coastal LA	1867	3581	1543
9	Downtown LA	1832	2569	1109
10	Riverside	1825	3411	1463
12	Sacramento	1877	2107	916

Table B- 4. Annual cost of operation in a single-family building using the current TOU rate structure - controlled scenarios

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	4807	4706	4704	4677	2157	2097	2037	2010
3	4359	4271	4283	4273	1986	1936	1898	1875
4	4144	4084	4056	4052	1875	1833	1792	1769
6	3573	3406	3542	3506	1602	1535	1564	1539
9	2614	2612	2588	2663	1185	1247	1135	1182
10	3392	3243	3380	3357	1519	1464	1481	1458
12	1986	1827	2031	1975	880	822	904	883

Table B- 5. Annual cost of operation in a multifamily-building using the proposed PG&E TOU rate structure - base case scenarios

Climate Zone	Representative City	NG ($/year)	ERWH ($/year)	HPWH ($/year)
1	Arcata	2042	4778	2040
3	San Francisco	1946	4358	1897
4	San Jose	1902	4132	1785
6	Coastal LA	1867	3989	1715
9	Downtown LA	1832	3801	1636
10	Riverside	1825	3786	1618
12	Sacramento	1877	4008	1722

Table B- 6. Annual cost of operation in a multifamily building using the proposed PG&E TOU rate structure - controlled scenarios

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	4916	4481	4833	4541	2192	1992	2097	1954
3	4452	4028	4414	4136	2015	1828	1956	1820
4	4224	3927	4170	3974	1895	1722	1848	1714
6	4044	3654	3991	3768	1812	1644	1771	1657
9	3855	3482	3813	3604	1729	1573	1689	1575
10	3815	3458	3792	3692	1712	1562	1670	1560
12	4080	3697	4025	3757	1825	1661	1782	1652

Table B- 7. Greenhouse Gas emissions from water heater operation in a multifamily building - base case scenario

Climate Zone	Representative City	NG (lb CO_2/year)	ERWH (lb CO_2/year)	HPWH (lb CO_2/year)
1	Arcata	19070	10855	4762
3	San Francisco	18172	9884	4399
4	San Jose	17767	9406	4152
6	Coastal LA	17436	9059	3992
9	Downtown LA	17112	8715	3800
10	Riverside	17048	8665	3757
12	Sacramento	17535	9133	4007

Table B- 8. Greenhouse Gas emissions from water heater operation in a multifamily building - controlled scenario

CZ	ERWH (3 to 6)	ERWH (10 to 1)	ERWH (mixed 3 to 6)	ERWH (mixed 10 to 1)	HPWH (3 to 6)	HPWH (10 to 1)	HPWH (mixed 3 to 6)	HPWH (mixed 10 to 1)
1	11547	10123	11455	10402	5300	4627	5090	4540
3	10593	9151	10598	9587	4916	4248	4789	4242
4	10058	9018	10064	9288	4660	4004	4539	4001
6	9639	8271	9687	8742	4458	3822	4370	3840
9	9235	7845	9298	8346	4263	3651	4189	3655
10	9141	7793	9223	8283	4226	3615	4149	3621
12	9762	8363	9773	8754	4493	3851	4394	3861

APPENDIX C

Appendix C: Energy load profiles for a single-family building. Includes daily average energy profiles for the three different water heater types (NGWH, ERWH, HPWH) in the building energy modeling of a single-family residence.

Climate Zone 3

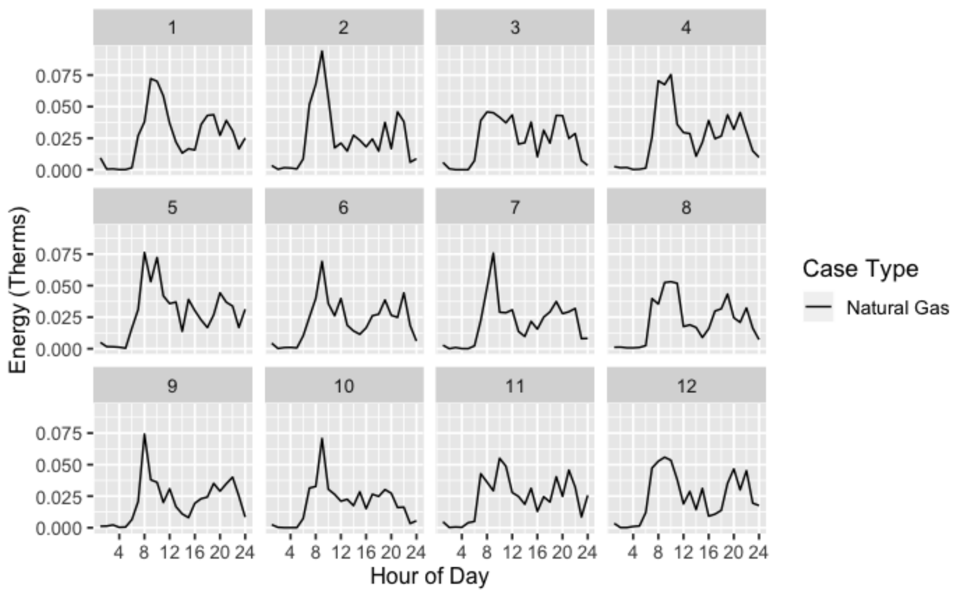

Figure C- 1. Natural gas consmption in an average day per month for NGWH in a single family builidng in climate zone 3.

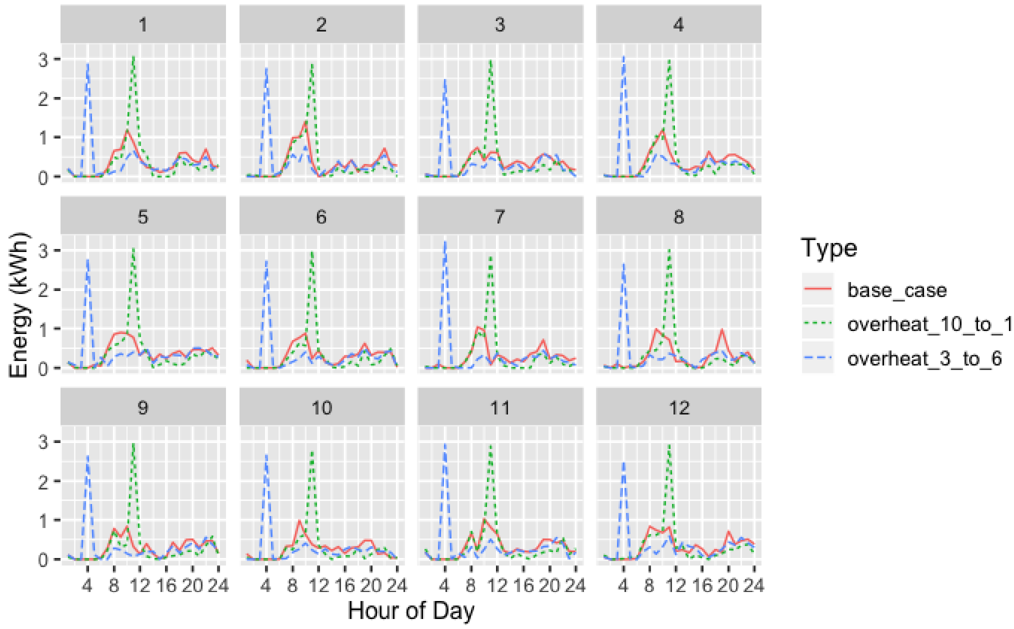

Figure C- 2. Electricity consumption in an average day per month for an ERWH in a single-family building in climate zone 3.

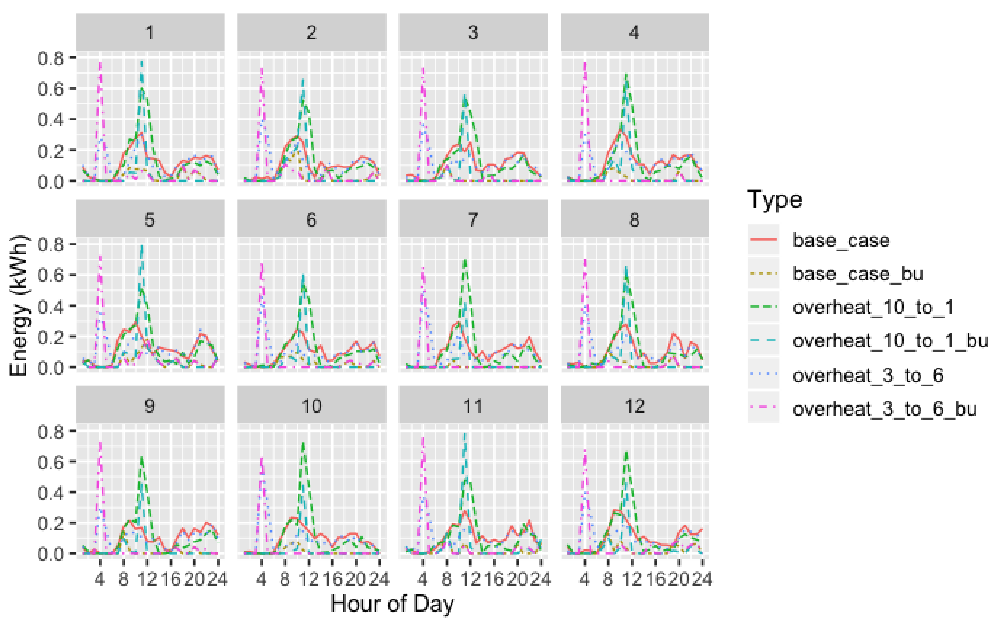

Figure C- 3. Electricity consumption in an average day per month for an HPWH in a single family builidng in climate zone 3.

Climate Zone 4

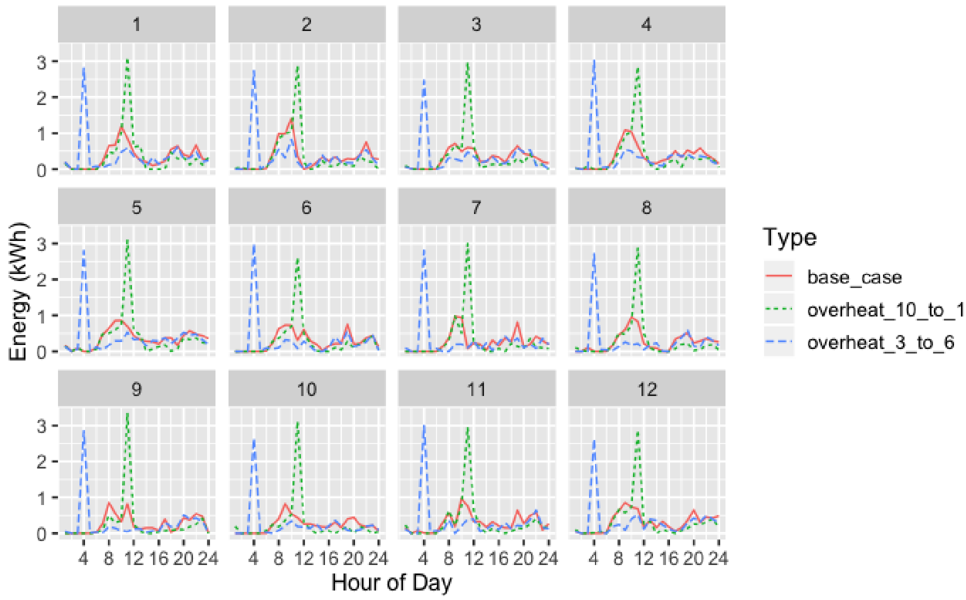

Figure C- 4. Electricity consumption in an average day per month for an ERWH in a single-family building in climate zone 4.

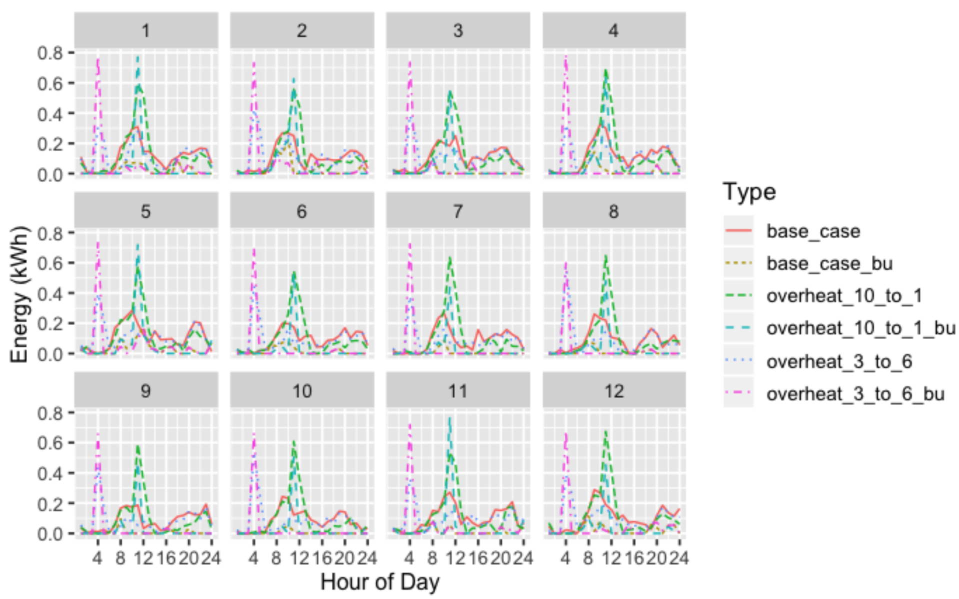

Figure C- 5. Electricity consumption in an average day per month for an HPWH in a single family builidng in climate zone 4.

Climate Zone 6

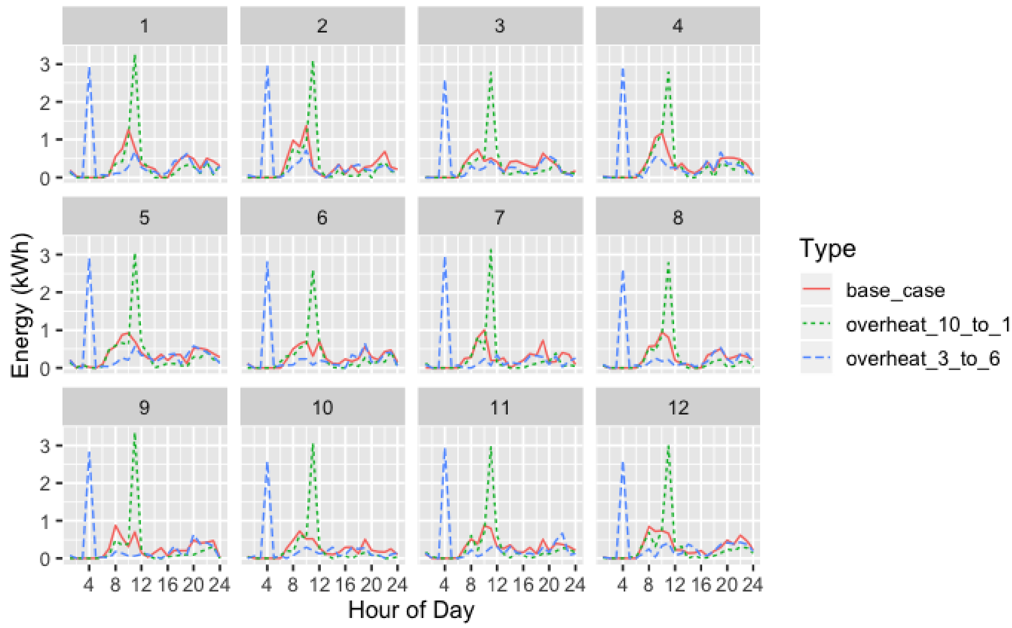

Figure C- 6. Electricity consumption in an average day per month for an ERWH in a single-family building in climate zone 6.

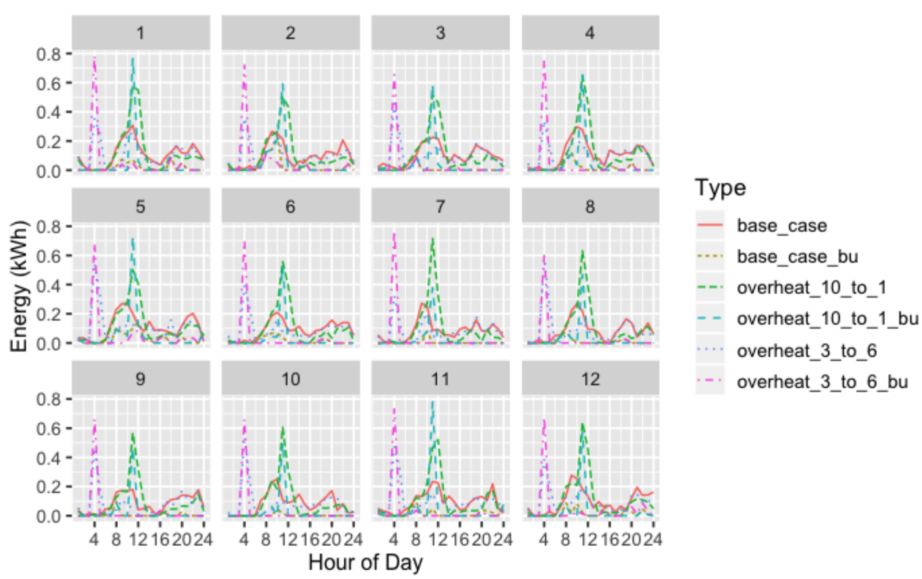

Figure C- 7. Electricity consumption in an average day per month for an HPWH in a single family builidng in climate zone 6.

Climate Zone 9

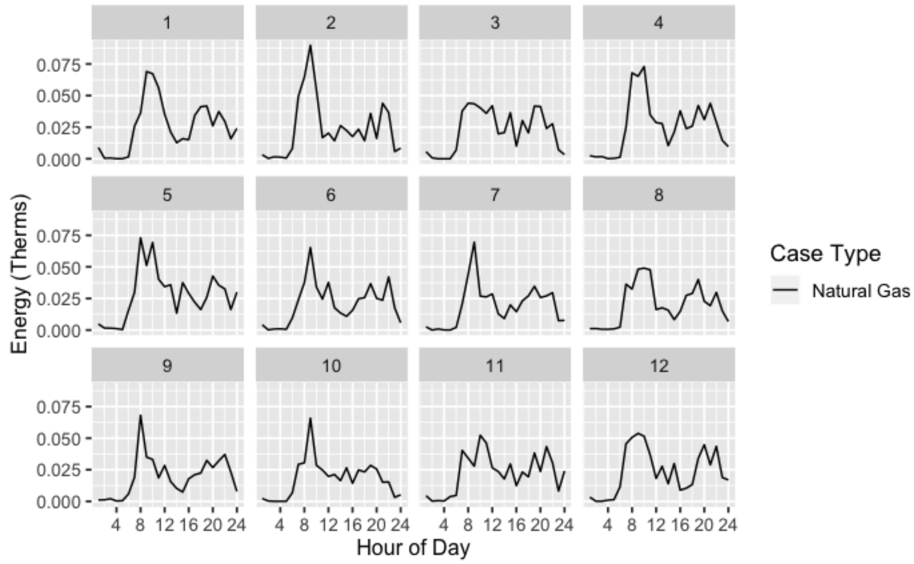

Figure C- 8. Natural gas consmption in an average day per month for NGWH in a single family builidng in climate zone 9.

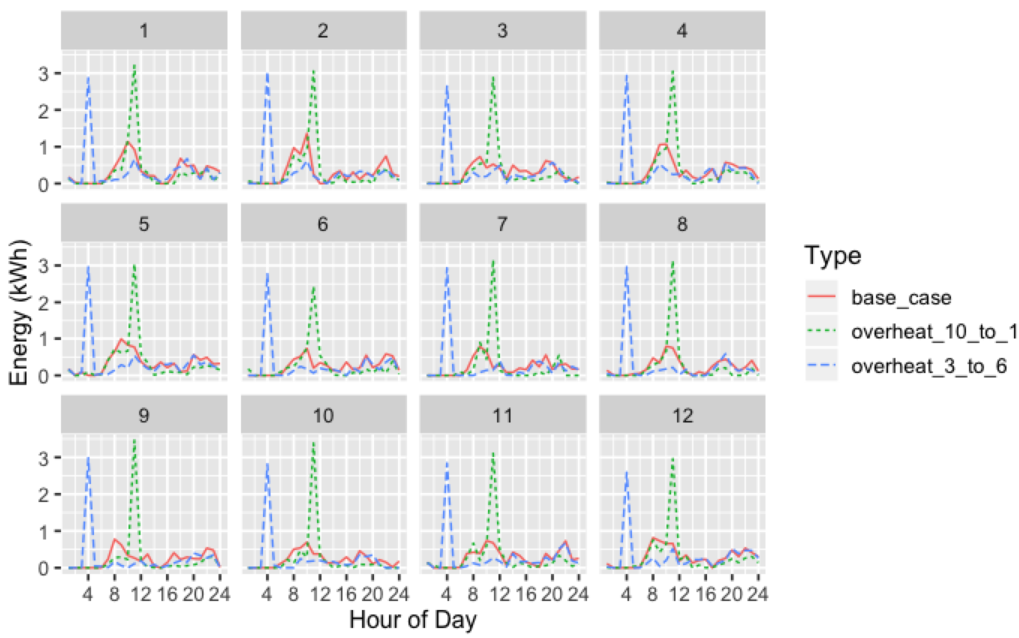

Figure C- 9. Electricity consumption in an average day per month for an ERWH in a single-family building in climate zone 9.

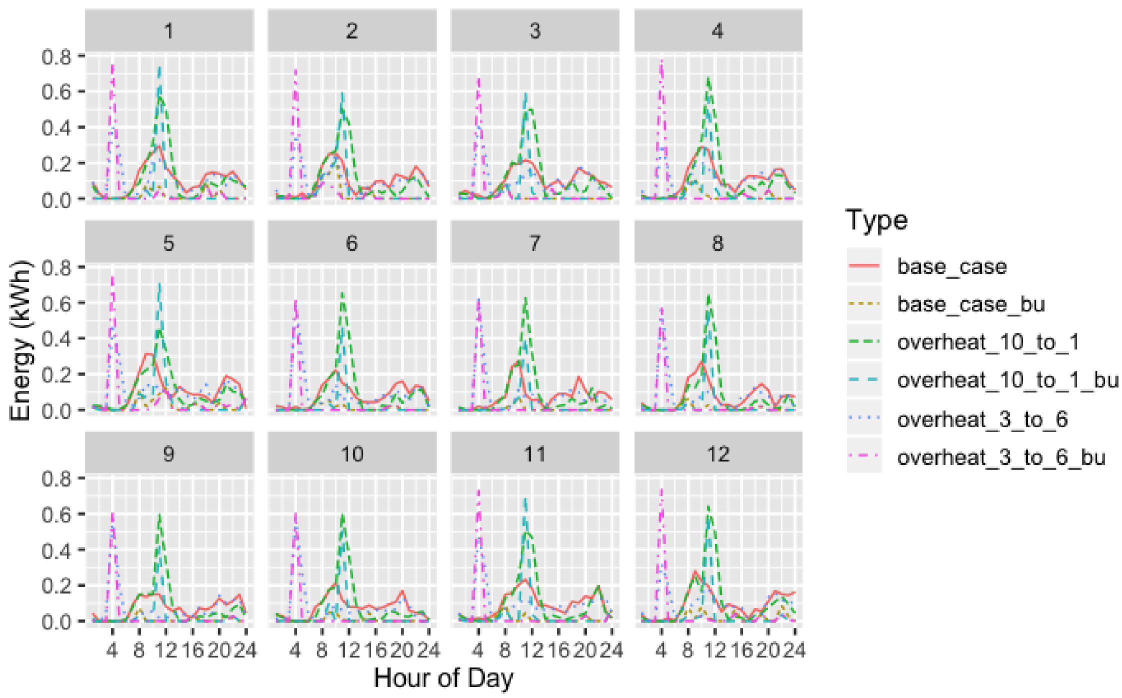

Figure C- 10. Electricity consumption in an average day per month for an HPWH in a single family builidng in climate zone 9.

Climate Zone 10

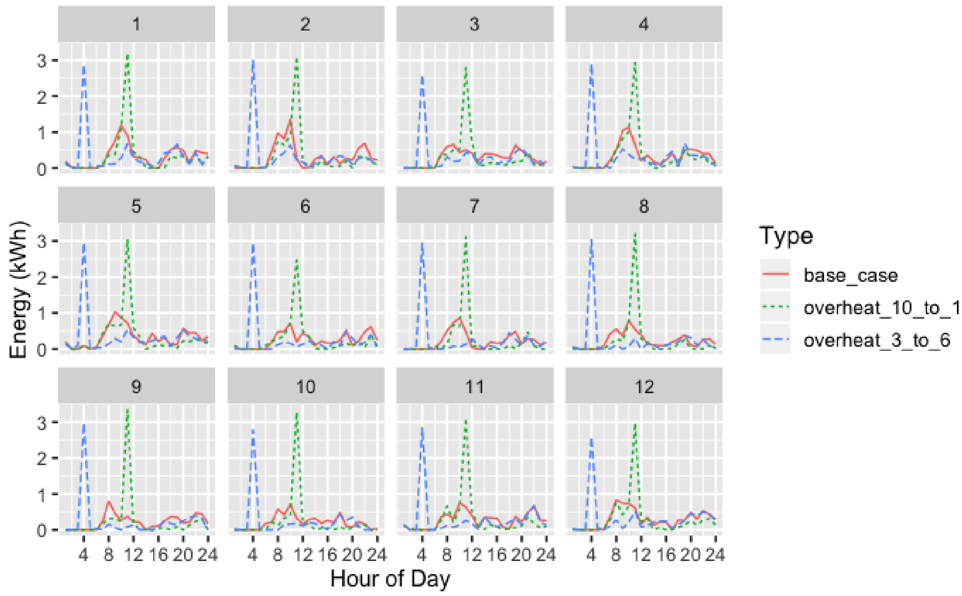

Figure C- 11. Electricity consumption in an average day per month for an ERWH in a single-family building in climate zone 10.

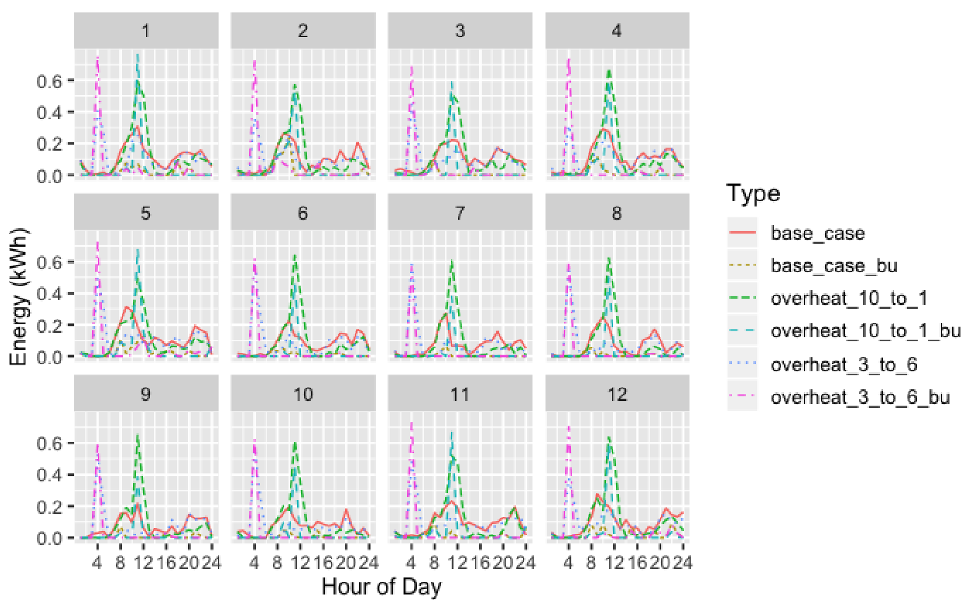

Figure C- 12. Electricity consumption in an average day per month for an HPWH in a single family builidng in climate zone 10.

Climate Zone 12

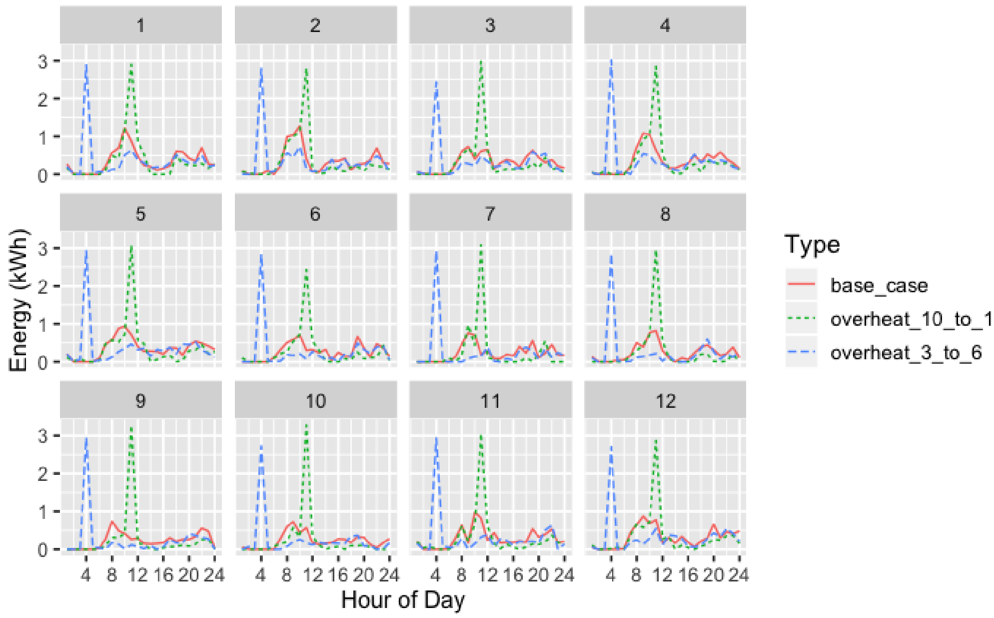

Figure C- 13. Electricity consumption in an average day per month for an ERWH in a single-family building in climate zone 12.

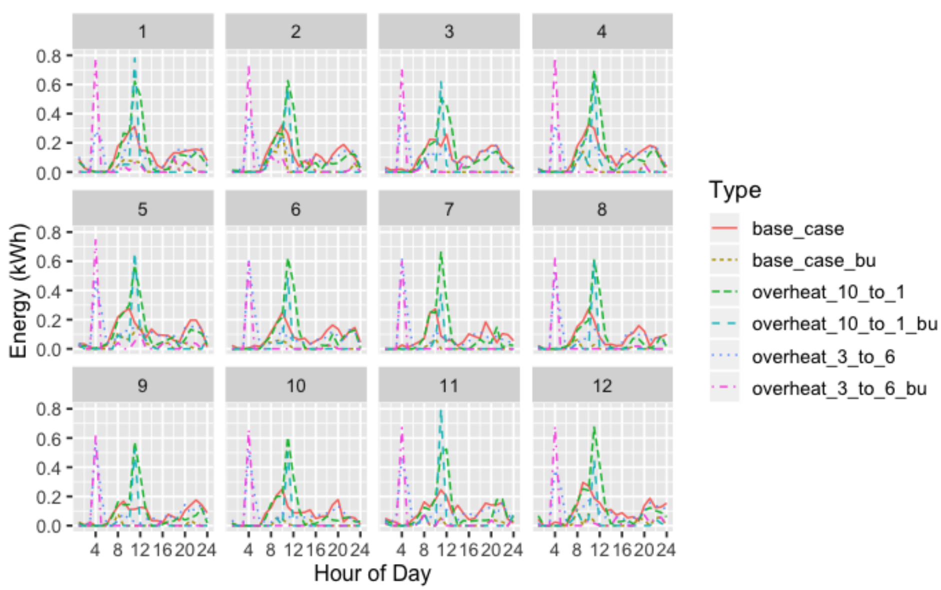

Figure C- 14. Electricity consumption in an average day per month for an HPWH in a single family builidng in climate zone 12.

APPENDIX D

Appendix D: Power generation and type of generation source per climate zone.

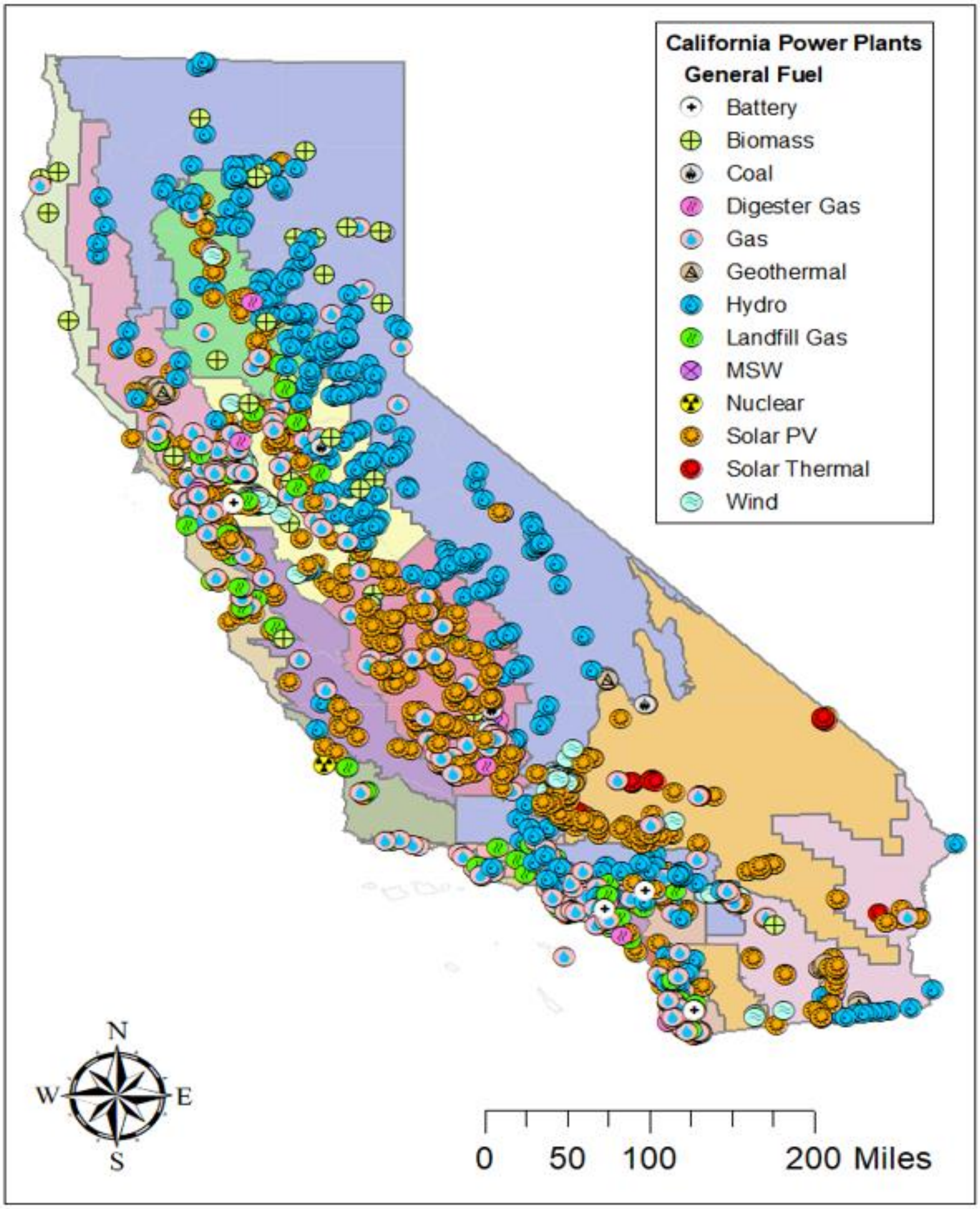

Figure D- 1. Power generation in California by type and by climate zone. (CEC, 2018)

APPENDIX E

Appendix E: Climate Zone Rank of monthly average building electricity and natural gas consumption,

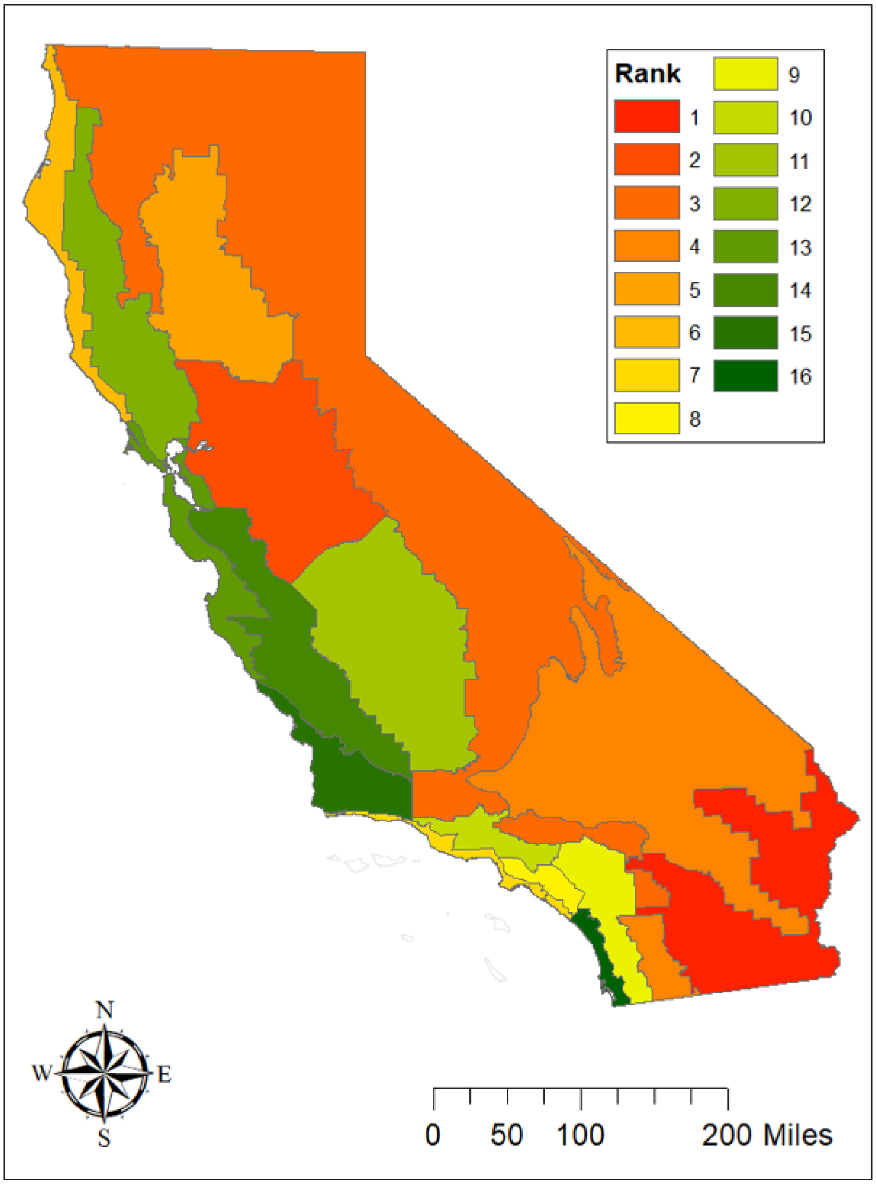

Figure E- 1. Rank of monthly average building electricity consumption per Climate Zone. Climate Zone 15 has the highest rate of consumption, while climate zone 7 has the lowest.

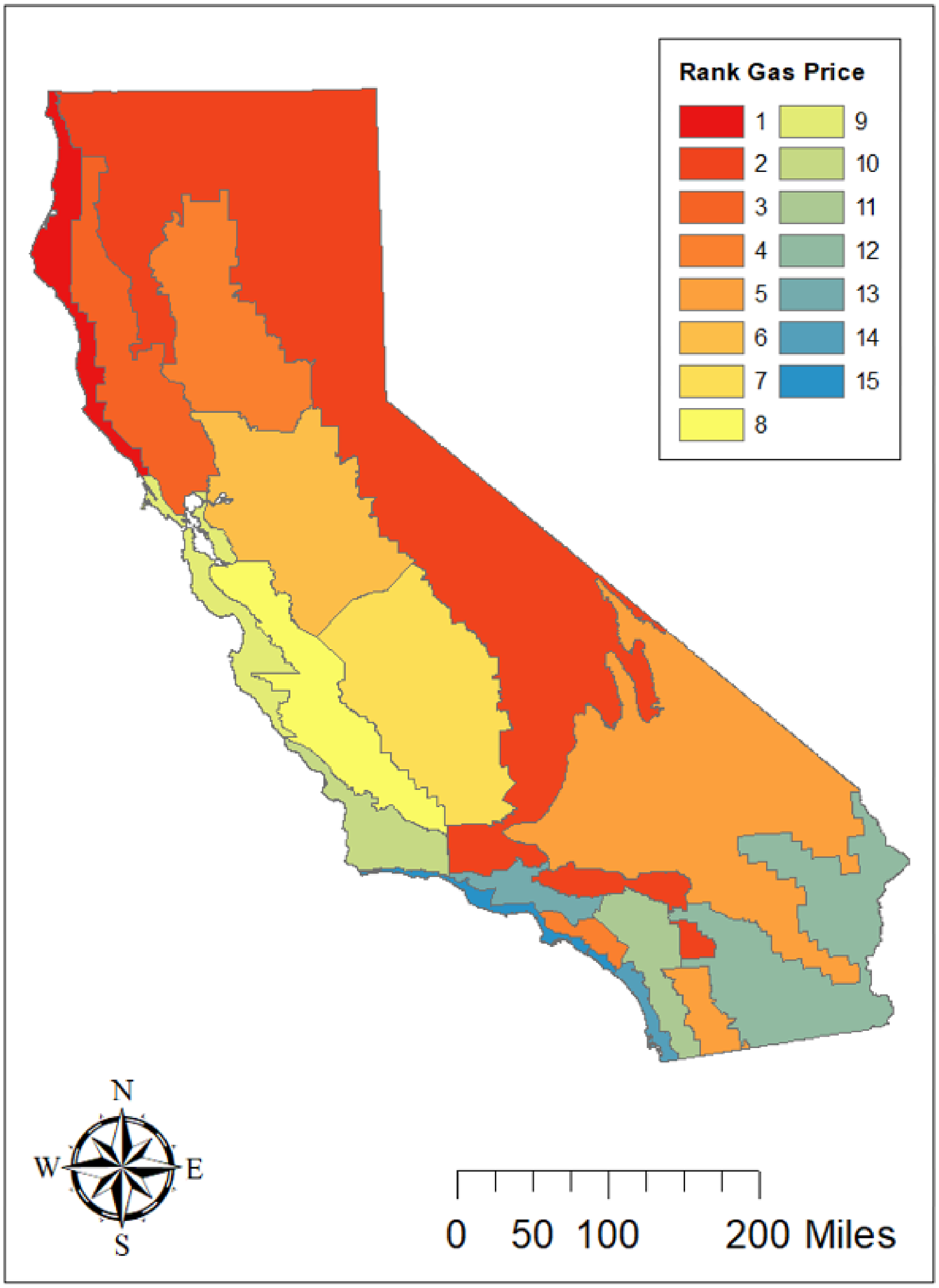

Figure E- 2. Rank of monthly average cost for utility natural gas consumption per Climate Zone. Climate Zone 1 has the highest rate of consumption, while climate zone 6 has the lowest.